

**Provenance of a large Lower Cretaceous turbidite submarine fan complex on the active
Laurasian margin: Central Pontides, northern Turkey**

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Abstract

The Pontides formed the southern active margin of Laurasia during the Mesozoic. They became separated from mainland Laurasia during the Late Cretaceous, with the opening of the Black Sea as an oceanic back-arc basin. During the Early Cretaceous, a large submarine turbidite fan complex developed in the Central Pontides. The turbidites cover an area of 400 km by 90 km with a thickness of more than 2 km. We have investigated the provenance of these turbidites—the Çağlayan Formation—using paleocurrent measurements, U-Pb detrital zircon ages, REE abundances of dated zircons and geochemistry of detrital rutile grains. 1924 paleocurrent measurements from 96 outcrop stations indicate flow direction from northwest to southeast in the eastern part of the Çağlayan Basin and from north-northeast to west-southwest in the western part. 1194 detrital zircon ages from 13 Lower Cretaceous sandstone samples show different patterns in the eastern, central and western parts of the basin. The majority of the U-Pb detrital zircon ages in the eastern part of the basin are Archean and Paleoproterozoic (61% of all zircon ages, 337 grains); rocks of these ages are absent in the Pontides and present in the Ukrainian Shield, which indicates a source north of the Black Sea. In the western part of the basin the majority of the zircons are Carboniferous and Neoproterozoic (68%, 246 grains) implying more local sources within the Pontides. The detrital zircons from the central part show an age spectrum as mixture of zircons from western and eastern parts. Significantly, Jurassic and Early Cretaceous zircons make up less than 2% of the total zircon population, which implies lack of a coeval magmatic arc in the region. This is compatible with the absence of the Lower Cretaceous granites in the Pontides. Thus, although the Çağlayan Basin occupied a fore-arc position above the subduction zone, the arc was missing, probably due to flat subduction, and the basin was

largely fed from the Ukrainian Shield in the north. This also indicates that the Black Sea opened after the Early Cretaceous following the deposition of the Çağlayan Formation.

Keywords: Black Sea, Central Pontides, Early Cretaceous, paleocurrent, provenance, detrital zircon.

1. Introduction

During the Mesozoic, the Pontides formed the active margin of Laurasia, with the Tethys ocean dipping north under the Pontides along the present İzmir-Ankara-Erzincan Suture (e.g., Şengör and Yılmaz, 1981; Okay and Nikishin, 2015). The subduction resulted in the formation of Middle-Late Jurassic and Late Cretaceous magmatic arcs in the Pontides. Between these magmatic events, a large submarine turbidite basin formed in the Central Pontides during the Early Cretaceous. Northward subduction of the Tethyan ocean during the deposition of the turbidites is shown by the presence of subduction-accretion complexes in the southern part of the Central Pontides (called the Central Pontide Supercomplex) with Early Cretaceous (136-102 Ma) greenschist, blueschist and eclogite facies metamorphism (Okay et al., 2006a, 2013; Aygül et al., 2015, 2016). However, there is no evidence for a contemporaneous magmatic arc development in the Central Pontides or to the north. The basinal sediments, called the Çağlayan Formation, occupy an area of 400 km by 90 km and with a thickness of over two kilometers (this study and Okay et al., 2013). We provide data on the provenance of these turbidites from paleocurrent measurements, U-Pb detrital zircon ages and detrital rutile geochemistry from the sandstones, and discuss the source of the turbidites and their relation to the opening of the Black Sea Basin. The Black Sea is a back-

arc basin with oceanic crust, which opened during the Late Cretaceous and separated the Pontides from the mainland Laurasia (Nikishin et al., 2015a).

Large turbidite fans are commonly deposited on passive continental margins at shelf edges and are fed by a point source (often a submarine canyon) (e.g., Rupke, 1978; Reading and Richards, 1994). The Çağlayan turbidite fan complex, that formed on an active continental margin above a subduction zone (Okay et al., 2013) and was fed by multiple sources, differs with its size (400 km by 90 km) from the known fans that formed on active margins (e.g., Shanmugam and Moiola, 1988; Mattern, 2005). It occupied the position of a fore-arc, such as the Great Valley Basin in California (e.g. Ingersoll, 1979), yet unlike typical fore-arc basin strata, the Lower Cretaceous Çağlayan Formation has very minor amounts of syn-depositional detrital zircons and is devoid of volcanic rock fragments. This is compatible with the absence of an Early Cretaceous arc in the Black Sea region. The amount of syn-depositional detrital zircons is higher than 80% in the fore-arc basinal strata in the western US (e.g., Sharman et al. 2015). Thus, the Çağlayan Basin provides an unusual example of a basin at an active continental margin, which has features of a submarine fan complex deposited at a passive continental margin.

2. Geology of the tectonic units of the Central Pontides

The Pontides form an E–W trending mountain range between the Black Sea to the north and the İzmir-Ankara Suture to the south (Fig. 1). They consist of three distinct terranes, called the Sakarya, Istanbul and Strandja Zones (Okay and Tüysüz, 1999). The Lower Cretaceous shelf and turbidite sequence occupy a large area in the Central Pontides, covering both Istanbul and Sakarya Zones. The main features of these terranes are described below as a basis for the discussion of the detrital zircon data.

2.1. The Istanbul Zone

The Istanbul Zone is characterized by a continuous, well-developed, transgressive Paleozoic sedimentary succession ranging from Ordovician to Carboniferous (Görür et al., 1997; Dean et al., 2000; Özgül, 2012), which lies over a late Neoproterozoic granitic and metamorphic basement (Chen et al., 2002) (Figs. 2 and 3). The late Neoproterozoic crystalline basement consists of gneiss, amphibolite, metaophiolite, metavolcanic and metasedimentary rocks and many granitic plutons dated 560–590 Ma (Yiğitbaş et al., 1999, 2004; Ustaömer P. and Rogers, 1999; Chen et al., 2002; Ustaömer P. et al., 2005; Okay et al., 2008). The Paleozoic rocks of the Istanbul Zone were deformed during the Carboniferous Variscan Orogeny and were intruded by the latest Permian (255–261 Ma) granites (Yılmaz-Şahin et al., 2009; Ustaömer P. et al., 2005; Okay et al., 2013) (Figs. 2 and 3). The Paleozoic sequence of the Istanbul Zone is unconformably overlain by the Permo–Triassic sedimentary rocks. In the eastern part of the Istanbul Zone in the Central Pontides Upper Jurassic–Lower Cretaceous shallow marine platform carbonates lie unconformably over the Permo–Triassic series; the same limestones extend east to the Sakarya Zone providing an upper age limit for the juxtaposition of these two terrains. The Upper Jurassic–Lower Cretaceous limestones are unconformably overlain by the Lower Cretaceous shelf clastic and carbonate sequences and by the siliciclastic turbidites of the Çağlayan Formation, which also extend both over the Istanbul and Sakarya Zones (Figs. 1, 2 and 3).

2.2. The Sakarya Zone

The Sakarya Zone has a pre-Jurassic basement consisting of two main components. The continental part of the basement is made up of metamorphic rocks intruded by the

Devonian, Carboniferous and Permian granites (Okay, 1996; Okay et al., 1996; 2006a, b; Ustaömer P. et al., 2012; Ustaömer et al., 2012; Aysal et al., 2012; Sunal, 2013; Nzegge et al., 2006; Topuz et al., 2004, 2007, 2010; Dokuz, 2011; Kaygusuz et al., 2012) (Fig. 2). The other part of the basement consists of the Permo–Triassic accretionary complexes, called the Karakaya Complex (Okay and Göncüoğlu, 2004). The Karakaya Complex is subdivided into a lower part made up of metabasites with Late Triassic eclogite and blueschist tectonic slices (Okay and Monié 1997; Okay et al., 2002), and an upper part of chaotically deformed greywackes and basalts with exotic Permo–Carboniferous limestone blocks. The Triassic Küre Complex in the Central Pontides, consisting of the Upper Triassic flysch with serpentine, pillow lava and dolerites (Ustaömer and Robertson, 1994) can be correlated with the Upper Karakaya Complex. The basement rocks of the Sakarya Zone are overlain by Lower Jurassic sandstone and conglomerate, which pass up into a thick series of volcanoclastic and volcanic rocks of Lower–Middle Jurassic age (Kandemir and Yılmaz, 2009; Genç and Tüysüz, 2010). High-level, acidic to intermediate intrusions of Middle Jurassic age crop out widely in the Central Pontides (Yılmaz and Boztuğ, 1986; Okay et al., 2013, 2014). The Middle Jurassic magmatic rocks in the Central Pontides are unconformably overlain by Upper Jurassic–Lower Cretaceous carbonates and by the Lower Cretaceous turbidites of the Çağlayan Formation, which extend west to the Istanbul Zone (Tüysüz, 1999; Hippolyte, et al., 2010) (Fig. 3).

3. Lower Cretaceous clastic sequence of the Central Pontides

The Lower Cretaceous turbidites are bounded in the north by the Black Sea Basin and in the south by a large area of Jurassic–Cretaceous accretionary complex, the Central Pontide Supercomplex, which is associated with the İzmir-Ankara Suture (Okay et al., 2013). The Lower Cretaceous clastic sequence (the Çağlayan Formation) of the Central Pontides can be

divided into a shelf sequence exposed along the western Black Sea margin and a deep marine turbidite system that crops out over a wide area in the Central Pontides (Fig. 1).

3.1. Lower Cretaceous shelf deposits

The Lower Cretaceous (Barremian-Albian) shelf sediments are exposed along the southern coast of the Black Sea in the Central Pontides (Figs. 1 and 2), where they lie unconformably over the Upper Paleozoic and Triassic sedimentary rocks (Figs. 1 and 3). The sequence begins with white clean quartz arenites (Velibey Formation) which pass laterally and upwards into rudist-bearing shallow marine limestones of Barremian-Aptian age (Varol and Akman, 1988; Tüysüz et al., 2004; Yılmaz and Altınır, 2007; Masse et al., 2009; Hippolyte et al., 2010) (Fig. 4a and b). The limestones are conformably overlain by glauconite-bearing dark sandstones and siltstones, which pass into the black Aptian–Albian shales (Görür et al., 1993; Hippolyte et al., 2010). The sequence ends with Albian shallow marine to continental sandstone and shale with coal horizons (Hippolyte et al., 2010).

3.2. Lower Cretaceous turbidites

The Lower Cretaceous (Barremian-Late Aptian) turbidites, called the Çağlayan Formation, crop out over an area of 400 km by 90 km in the Central Pontides and have a thickness of over 2000 meters (Tüysüz, 1999; Derman, 2002; Hippolyte et al., 2010; Okay et al., 2013) (Figs. 3 and 4c). They consist mainly of an intercalation of medium grained sandstone and shale (Fig. 4c and d). The basin itself shows deepening character to south having finer grain size and thinner beds well as increasing shale/sandstone ratio. The sandstones display typical turbidite features including graded bedding, cross bedding, abundant slumps, debris flows, and sole marks (Fig. 4e). The sandstone–shale sequence commonly includes mass

flow horizons ranging from debris flows to olistostromes (Fig. 4f). The debris flows are more common in the western part of the basin. The clasts in the debris flows and olistostromes are mainly Upper Jurassic–Lower Cretaceous limestones with lesser blocks of Paleozoic and Triassic sedimentary rocks, and Jurassic dacite. The limestone blocks may reach up to a few kilometers across. Distal parts of the Çağlayan Formation is strongly deformed by folding and thrusting, and in the south it shows low-grade metamorphism dated using laserprobe technique on muscovites as Early Cretaceous (112–102 Ma, Okay et al., 2013). The Çağlayan Formation rests unconformably over various units, including the Paleozoic and Triassic sedimentary rocks and the Upper Jurassic–Lower Cretaceous shallow marine limestones, and is unconformably overlain by the Upper Cretaceous (Santonian) pelagic limestones (Okay et al., 2013) (Fig. 3). The depositional age of the Çağlayan Formation is constrained to Barremian–Late Aptian based on nannoplanktons (Hippolyte et al., 2010). The same interval is represented by hemipelagic limestone deposition in the western Sakarya Zone and by a stratigraphic gap in the Eastern Pontides (Okay and Şahintürk, 1997; Altıner et al., 1991).

4. The provenance of the Lower Cretaceous turbidites

The metamorphic area in the Central Pontides south of the Çağlayan Formation in the Central Pontides was previously considered as a pre-Jurassic basement, and thus could have constituted a potential source area for the Lower Cretaceous turbidites. However, recent studies have shown that this region (the Central Pontide Supercomplex) consists of subduction-accretion complexes mainly of Early Cretaceous age (Okay et al., 2013), and thus an unlikely source for the Çağlayan Formation. They were accreted before or during the deposition of the Çağlayan Formation. We investigated the provenance of the Lower

Cretaceous turbidites through the paleo-current analysis, U-Pb detrital zircon dating and detrital rutile geochemistry.

4.1. The paleocurrent analysis

The paleocurrent analysis is based on 1924 measurements in 96 outcrop stations over an area of 400 km by 90 km (Fig. 5). Measurements include mainly unidirectional indicators from flute casts (1308) and cross beddings (34), and bidirectional (linear) indicators from groove casts (582). All measurements are corrected for tectonic tilting. There is no cleavage development in the bulk of the Çağlayan Formation and no other evidence for ductile deformation; the folding was cylindrical and involved buckling, which allows restoration of the paleocurrents to their original position. We avoided measuring paleocurrent directions in outcrops where the strata were strongly deformed and folded, especially in the southern parts of the basin. Fig. 5 shows the paleocurrents from the Lower Cretaceous turbidites. The 96 outcrop stations are reduced to 30 by combining the nearby stations with an average separation of 3 km and which have similar paleocurrent directions. Data from each station, as well as information on the location and sedimentological features of each outcrop, are given in Appendix A and the methods are given in Appendix B.1. The paleocurrent data from the Çağlayan Formation can be divided into three gradational areas in the Central Pontides. In the east, almost all of the measured paleocurrents are from the northwest to the southeast (Fig. 5); in the central part, the paleocurrents are more varied with both southward and northward directed paleocurrents. In the west, the paleocurrents are generally to the south, although some indicate northward flow.

The Central Pontides form a broad arc, which was produced through oroclinal bending during the Late Cretaceous to Eocene as a result of continental collision with the Kırşehir

Massif (Meijers et al., 2010b). Paleomagnetic data indicate anticlockwise and clockwise rotations of up to 30° in the eastern and western parts of the Central Pontides and no rotation in the central part of the Central Pontides. Fig. 6 shows the paleocurrents that are restored to their pre-Late Cretaceous positions. In their pre-Cretaceous positions, the paleocurrents are more axial with east-southeasterly flow in the eastern part of the basin and predominantly southwestward flow in the west. The picture is that of a large submarine fan feeding from the north (Fig. 2).

4.2. U–Pb ages of detrital zircons from the Lower Cretaceous sandstones

Detrital zircon ages are widely used for provenance analysis to constrain paleogeography, tectonic reconstructions, and crustal evolution (e.g., Gehrels et al., 1995; Fedo et al., 2003; Okay N. et al., 2010; Jacobson et al., 2011; Meinhold et al., 2013). In this study we have used detrital zircon ages from 13 sandstone samples from the Lower Cretaceous sequence of the Central Pontides. These include newly determined zircon ages from nine sandstone samples, as well as zircons from four samples published by Okay et al. (2013). Two of 13 samples are shelf quartz arenites of the Velibey Formation (samples 1A and T23) and the remaining are turbiditic sandstones. The samples from turbiditic part of the basin were collected over an east-west distance of 400 km (Fig. 5), two are from the west (samples 13 and 22A), four from the center (samples 2221, 2640, 2721 and 2239) and five from the east (samples T2, T3, T9, T11 and 38). The petrography of the samples is described in Appendix C and their UTM coordinates are given in Table 1. The relative stratigraphic locations of the samples are not clear because of strong folding and faulting in the Çağlayan Formation, the large area of sampling and the considerable sedimentary thickness.

1348 detrital zircon ages have been obtained from 13 sandstone samples of which 1194 (89% of all zircons) are concordant at 90–110%. Among these 80 concordant detrital zircon ages obtained from sample 1A, 168 ages from sample T23, 74 ages from sample 13 and 43 ages from sample 22A representing the western part of the basin. 63 concordant detrital zircon ages from sample 2221, 89 ages from sample 2239, 51 ages from sample 2640 and 74 ages from sample 2721 represent the central part of the basin. We have 158 concordant detrital zircon ages from sample T2, 165 ages from sample T3, 77 ages from sample T9, 85 ages from sample T11 and 67 ages from sample 38 representing the eastern part of the basin.

The analytical methods are given in Appendix B.3 and the U–Pb data in Appendix D. Fig. 7 shows the age distribution of 1194 zircons. There are three main and four minor peaks. The main peaks are at Carboniferous–Permian (252–356 Ma; 26%, 308 grains), Paleoproterozoic (1700–2200 Ma; 17%; 208 grains) and Archean (2750–3000 Ma; 15%; 185 grains). The subsidiary peaks are late Neoproterozoic–Cambrian (525–650 Ma; 9%; 104 grains), Triassic (6%, 76 grains), late Mesoproterozoic–early Neoproterozoic (875–1100 Ma; 4%; 48 grains) and Silurian (2%; 22 grains). Zircon ages from the western, central and eastern parts of the Çağlayan Formation show different patterns and will be discussed separately below (Fig. 8). Four samples from the western part of the Çağlayan Formation yielded 365 concordant detrital zircon ages (Fig. 9). Two samples (1A and 23) are quartz arenites from the Velibey Formation from the shelf sequence, the other two (13 and 22A) are from turbiditic sandstones (Figs. 5 and 8, Table 1). Carboniferous (43% of the detrital zircons, 156 grains) and Neoproterozoic (25%, 90 grains) zircons dominate the zircon population from the western part of the Çağlayan Formation (Fig. 10). The Neoproterozoic zircons are predominantly late Neoproterozoic passing into early Cambrian (665–510 Ma; 27%, 97

zircons). There are few Paleoproterozoic (7%, 26 grains), Devonian (6%, 26 grains), Mesoproterozoic (4%, 13 grains) and Archean zircons (2%, 7 grains), no zircons of Jurassic age, and only two Triassic and Silurian zircon grains (Figs. 10 and 11).

From the central part of the Çağlayan Formation, 227 concordant detrital zircon ages were obtained from three turbiditic sandstone samples (2221, 2640 and 2721) and from one metasandstone (2239) sample. The metasandstone sample is from distal part of the Çağlayan Formation metamorphosed under low grade conditions (Okay et al., 2013) (Figs. 5 and 8, Table 1). The major zircon populations are Paleoproterozoic (2090–1730 Ma; 22%, 62 grains), Neoproterozoic (760–1070 Ma; 14%, 40 grains) and Triassic (15%, 41 grains) (Figs. 9 and 10).

From the eastern part of the Çağlayan Formation, 552 concordant detrital zircon ages were obtained from five turbiditic sandstone samples (T2, T3, T9, T11 and 38; Figs. 5 and 8, Table 1). Archean (38%, 209 grains), and Paleoproterozoic (23%, 128 grains) zircons are dominant followed by Permian (15%, 82 grains) and Triassic (6%, 34 grains) zircons. Rest of the ages show scattered distribution without significant clustering.

4.3. The Th/U ratios and REE contents of the detrital zircons

The Th/U ratio is the first order discriminant between igneous and metamorphic zircons (Hoskin and Ireland, 2000; Belousova et al., 2002; Rubatto, 2002). The metamorphic zircons have the Th/U ratios generally less than 0.1, whereas this value in igneous zircons is above 0.2 (Hoskin and Schaltegger, 2003; Rubatto, 2002; Vavra et al., 1999). The Th/U ratios of the analyzed zircons are predominantly above 0.1, which suggests a mainly magmatic origin (Fig. 12) with only a few number of metamorphic zircons. Most of the metamorphic zircons are from the central and eastern part, and are generally older than 1800 Ma (Fig. 12).

Rare earth elements (REE) are indicators of crystallization environments; they are considered incompatible for rock forming minerals during the crystallization of felsic magma and are accumulated in many accessory minerals such as zircon (Rollinson, 1993). REE abundances of detrital zircons from seven samples (1A, 13, 2221, 2721, 2640, 2239 and 38) are determined simultaneously along with their U–Pb ages using a laser ablation split stream petrochronology at UC Santa Barbara (following the procedure described by Kylander-Clark et al. (2013); for analytic methods and data sets see Appendix B.3. and E). Fig. 13 shows the REE patterns of detrital zircon from seven sandstone samples normalized to chondrite values of McDonough and Sun (1995). REE patterns of all samples show steeply rising slopes from LREE to HREE with more or less pronounced positive Ce and negative Eu anomalies suggesting an igneous origin (Fig. 13-a₁-g₁) (Rubatto, 2002; Hoskin and Schaltegger, 2003). Zircon grains with Th/U ratios in the range of 0.02–0.1 and with low total REE concentrations (<1000 ppm) are regarded as of metamorphic origin and are shown separately in Fig. 13. Some of metamorphic zircons show depleted MREE and HREE, which are typical for the zircons produced by sub-solidus growth with garnet; samples with these zircons (2239 and 2721) come from the central part (Fig. 13-a₂-g₂) (Rubatto, 2002). Zircons from mafic rocks are generally characterized by low total REE (<450 ppm) values, high Th/U ratios (>0.1) and depletion of HREE and MREE (Belousova et al., 1998, 2002); such zircons (3 of all zircon ages, 44 grains), shown in blue in Fig. 13, are concentrated in the central and eastern parts of the Çağlayan Formation, which may have originated from mafic rocks.

4.4. Detrital rutile geochemistry and thermometry

Rutile is mainly formed during medium-to high-grade metamorphism and is not usually abundant in igneous rocks (e.g., Force, 1980; Meinhold, 2010). It is chemically and physically

stable and is not affected by weathering, transport and diagenesis (e.g., Morton and Hallsworth, 1999), and therefore can provide important information about the source area of sedimentary rocks (e.g., Zack et al., 2004; Meinhold et al., 2008; Meinhold, 2010; Okay N. et al., 2010; Triebold et al., 2007; 2012). 269 detrital rutile grains from four samples across the basin (Fig. 5, 1A, 13, 2721 and 38) were analyzed with an electron microprobe (EMP) to constrain the metamorphic sources of the Lower Cretaceous deposits (see Appendix B.4 for analytical details). Detrital rutiles are mostly light brown, reddish brown and dark brown, subrounded to rounded. Compositions with unusually high or low oxide totals (9 grains with wt % of $99 <$ or > 101) and the brookite–anatase polymorphs (17 grains, following the discrimination procedure outlined in Triebold et al., 2011) were excluded from the analysis. In total 242 detrital rutile compositions were used for interpretation; 75 are from sample 1A, 69 from sample 13, 40 from sample 2721 and 58 from sample 38. Rutile growth temperatures, calculated using the calibration of Tomkins et al. (2007), range between 525–917 °C (Fig. 14, Appendix F). The lithology and metamorphic facies of the rutile-bearing host rocks were estimated using the Nb and Cr contents of the rutiles as outlined in Triebold et al. (2012). Most rutile grains have originated from metapelitic rocks of amphibolite facies (Fig. 14). Rutiles from granulite-facies rocks occur mainly in the central and western parts, where they make up 15 and 12% of the rutiles, respectively.

5. Discussion

Below we discuss the source of the Çağlayan Formation based on the paleocurrent measurements and detrital zircon and rutile data. Zircons are predominantly found in felsic plutonic rocks, as also reflected in the high Th/U values of the analyzed zircons (Fig. 12).

Therefore, the detrital zircon ages do not provide a true reflection of the lithologies in the

source area but rather that of the felsic igneous rocks in the source. However, the quartz-rich nature of the Çağlayan Formation sandstones suggests that felsic plutonic rocks were a major component in the source region. A second complication in the interpretation of the detrital zircon ages is that some of the zircons could be recycled from older clastic sequences. We checked this possibility by comparing the detrital zircon spectra from the Çağlayan Formation sandstones with those from other clastic units in the circum-Black Sea region (Karslıoğlu et al., 2012; Okay N. et al. 2010; Nikishin et al., 2015b; Ustaömer P. et al., 2011; Ustaömer et al., 2016).

Overall, the detrital zircon ages from the Çağlayan sandstones show four major peaks in Archean, Paleoproterozoic, late Neoproterozoic and Carboniferous–Permian (Fig. 7). The distribution of these peaks is, however, different between western, central and eastern parts of the Çağlayan Basin (Figs. 8 and 9). These peak ages as well as their possible source areas are discussed below.

5.1. Archean and Paleoproterozoic zircons

Archean and Paleoproterozoic zircons, make up 19% (229 grains) and 20% (235 grains) of the total detrital zircon population of the Çağlayan Formation, respectively (Fig. 7) but they are heavily concentrated in the eastern and central parts of the basin, where they constitute 61% (337 grains) and 34% (94 grains), respectively, of the total zircon population (Figs. 9 and 10). Archean and Paleoproterozoic rocks are unknown from the Pontides, whereas such rocks crop out widely in the Ukrainian Shield (e.g., Shchipansky and Bogdanova, 1996; Claesson et al., 2006; Bogdanova et al., 2008, 2010; Bibikova et al., 2015) (Figs. 1 and 2). Present day sands from the large rivers draining the East European Platform, contain dominant populations of Archean and Paleoproterozoic zircons (Safonova et al., 2010; Wang

et al., 2011). The absence of Archean–Paleoproterozoic rocks in the Pontides and their presence north of the Black Sea coupled with the southeasterly paleocurrents measured in the eastern and central parts of the Çağlayan Basin indicate that these parts of the basin were sourced from north of the Black Sea. The REE patterns of pre-1800 Ma zircons from mafic rocks and metamorphic rocks, and geochemistry of detrital rutiles indicate that the most probable source for the eastern and central parts of the Çağlayan Basin is the East European Platform, where intense granulite to amphibolite facies metamorphic events that predate 1800 Ma were reported (e.g., Shchipansky and Bogdanova, 1996; Claesson et al., 2006; Bogdanova et al., 2008; Bibikova et al., 2015 and references there in). This conclusion is independently supported by the paleogeographic maps showing the East European Platform as an erosional area during the early Cretaceous (Baraboshkin et al., 2003).

5.2. Late Neoproterozoic zircons

Late Neoproterozoic (700–541 Ma) zircons are significant in the western part but less so in the central and eastern part of the basin (Figs. 9 and 10). Late Neoproterozoic–Cambrian granites make up a major part of the basement of northern Gondwana and Gondwana-derived terranes, which include the Istanbul Zone, Strandja Massif and Moesia (590–560 Ma; Neubauer, 2002; Chen et al., 2002; Ustaömer P. et al., 2005; Yılmaz-Şahin et al., 2014; Okay and Nikishin, 2015). The closest outcrop of the Neoproterozoic basement is in the Bolu Massif of the Istanbul Zone (Fig. 2), where granites have ages of 576 to 565 Ma (Ustaömer P. et al., 2005). This, together with the variable paleocurrent directions in the western part of the basin and debris flows with large blocks from the basement rocks of the Istanbul Zone indicates local sources for this part of the basin.

5.3. Carboniferous–Permian zircons

Carboniferous (17%) and Permian (9%) zircons make up 26% of the total detrital zircon population (Fig. 7). Their distribution is uneven; in the western part of the basin the Carboniferous zircons make up 43% of the total zircon population; this decreases to 8 and 4% in the central and eastern parts, respectively (Fig. 10). In contrast, the Permian zircons increase from 1% to 7% and to 15% from west to east. However, it should be pointed out that 56% (60 of 107 grains) of Permian ages come from a single sample T3 (Fig. 11).

The closest outcrop of Carboniferous–Permian granites is in the northern part of the Central Pontides, where zircons from two granitic bodies yield zircon U–Pb ages straddling the Carboniferous–Permian boundary (303–291 Ma, Nzegge, 2008; Nzegge et al., 2006) (Fig. 2). Such granites could be the source of the Permian detrital zircons from the Çağlayan Formation, whose ages generally cluster at 270–298 Ma (Fig. 11). Detrital zircons from the Middle Jurassic–Neogene sandstones from Crimea also show Permian age peaks of 280 Ma and 247 Ma (Nikishin et al., 2015b).

Carboniferous and Permian granites crop out in the Strandja Massif, in the Sakarya Zone and in the Caucasus (Fig. 2). In the Sakarya Zone and in the Lesser Caucasus their ages range from 330 to 317 Ma (Topuz et al., 2007; 2010; Nzegge et al., 2006; Mayringer et al., 2011; Ustaömer P. et al., 2012; Ustaömer et al., 2012) while in the Strandja Massif and in the Balkanides they are younger, with an age range of 315–250 Ma (Sunal et al., 2006, 2008; Carrigan et al., 2005). 68% and 82% of all Carboniferous detrital zircons from central and eastern part of the basin, respectively, yielded ages mostly in the 300–330 Ma range. In contrast, 88% of all Carboniferous zircons from the western part of the basin are mostly in range of 330–357 Ma. Early Carboniferous granites of these ages are not known in the Pontides or in the Black Sea region. Detrital zircons of this age range are common in the

Carboniferous turbidites of the Istanbul Zone (Okay N. et al. 2010) and could have possibly been recycled into the Lower Cretaceous sandstones.

5.4. Other zircon ages

Triassic detrital zircons constitute 6% of the total detrital zircon population of the Çağlayan Formation (Fig. 7). They are mostly concentrated on the central and eastern parts of the basin (Fig. 10). Triassic detrital zircons are also common in the Triassic subduction accretion complexes (Karakaya Complex) of the Sakarya Zone (Ustaömer et al., 2016) and in the Triassic Akgöl flysch of Küre Complex of the Central Pontides (Karslıoğlu et al., 2012) and Tauric flysch of Crimea (Nikishin personal communication 2015). In the Jurassic and younger sediments of Crimea, the Lower Triassic zircons with a peak age of 247 Ma constitute an important population (Nikishin et al., 2015b). Despite the wide presence of Triassic zircons in the circum-Black Sea sandstones, Triassic granitic rocks are not known from outcrop in the Pontides, Caucasus or from the Balkans. A Triassic magmatic arc, however, most likely exist in the subsurface beneath the Tertiary sediments in north of the Black Sea (Okay et al., 2013; Ustaömer et al., 2016) (Fig. 2). The Triassic detrital zircons in the Çağlayan Formation have most probably derived from this Triassic arc, although part of the Triassic zircons could also have been recycled from the Triassic Akgöl and Tauric flysch.

The amount of Ordovician, Silurian and Devonian detrital zircons in the Çağlayan Formation does not exceed a few percent (Fig. 7). Jurassic detrital zircons make up only 2% of the total zircon population, despite widespread outcrops of Middle Jurassic granites and porphyries in the Central Pontides (Yılmaz and Boztuğ, 1986; Nzegge, 2008; Okay et al., 2014). This shows that these intrusives were not exposed in the Early Cretaceous. The Lower Cretaceous detrital zircons are virtually absent, which argues against the presence of an Early

Cretaceous magmatic arc north of the Black Sea contrary to the suggestion of Nikishin et al. (2015a, b).

In summary, the paleocurrent and detrital zircon data show that the eastern and central parts of the Çağlayan Basin were fed from the East European Platform from the north, whereas more local sources, dominated by Carboniferous granites, were important for the western part of the basin.

The importance of the local sources in the western part of the basin is also shown by the abundance of, debris flows with blocks of Upper Jurassic limestones, Triassic and Paleozoic sandstones in this part of the basin. The debris flow conglomerates and sandstones of the western part also have metamorphic rock fragments, and detrital epidote and garnet which are not observed in the eastern part (Fig. 4f and Appendix C). Poorly sorted semi-angular shaped clasts of the conglomerates (Fig. 4f) and the large size of the olistoliths, locally reaching up to one kilometer or more, indicate short transport distance. They must have been derived from locally uplifted parts of the basement. Differences in the source between different parts of the Çağlayan Basin may suggest more than one river system flowing north to south to the Çağlayan Basin forming a fan complex, consisting of several coalescing fan systems (Fig. 15a). A lesser possibility is a large submarine system fan fed by a single river with local sources from fault blocks in the western part of the basin (Fig. 15b).

The Central Pontide Supercomplex south of the Çağlayan Formation predominantly consists of Early Cretaceous subduction-accretion complexes with eclogites and blueschists with 136-102 Ma metamorphic ages ($^{40}\text{Ar}/^{39}\text{Ar}$ mica ages; Okay et al., 2006a, 2013; Aygöl et al., 2015, 2016) (Figs. 1 and 15). Thus, Tethys Ocean was subducting northward during the deposition of the Çağlayan Formation. The southern distal parts of the Çağlayan turbidites were also subducted and metamorphosed; the white mica $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the phyllites and slates

from this part of the Lower Cretaceous turbidites are 106–112 Ma (Okay et al., 2013).

Sample 2239 is a metasandstone yielding post Jurassic detrital zircon ages similar to other samples, represents the metamorphosed distal parts of the Çağlayan Formation (Okay et al., 2013; Fig. 5, 8 and 11). This shows that the Çağlayan Basin was in a convergent margin setting similar to fore-arc basins. However, Early Cretaceous zircons are very rare in the Çağlayan Formation (less than 1%) and no Lower Cretaceous granites are known in the Central Pontides or from the northern margin of the Black Sea. This indicates that a magmatic arc did not develop during the Early Cretaceous, possibly because of flat-subduction (Fig. 16). The subduction-accretion of the Çangaldağ and Domuzdağı oceanic plateaus may have resulted in the flat subduction (Okay et al., 2013). Flat subduction of young oceanic crust with aseismic ridges, oceanic plateaus or seamount chains typically coincides spatially and temporally with the absence of arc volcanism, intense normal faulting of the fore-arc block and local block uplifts in the hinterland (e.g., Dickinson and Snyder, 1978; McGearry et al., 1985; Cloos, 1993; van Hunen et al., 2002), which is compatible with the Early Cretaceous tectonic setting of the Black Sea region. Although flat-slab subduction occurs at about 10% of the modern convergent margins (Gutscher et al., 2000), its effects on the sedimentation in the convergent margins are rare (e.g., Kortyna et al., 2014; Finzel et al., 2015). The Lower Cretaceous fan complex is a good example showing the effects of volcanic gap due to flat subduction processes on sedimentation; having no volcanic rock fragments in the sandstones, almost no coeval detrital zircons with sedimentation and no dykes cross cutting the strata.

In the Central Pontides and in Crimea there are no known outcrops of the Lower Cretaceous granitic or volcanic rocks (e.g., Nikishin et al., 2015b). Nikishin et al. (2015a) show Albian volcanic centers in the Black Sea offshore but these are not reflected in the sedimentary

record of the Early Cretaceous turbidites and need to be confirmed. The magmatic arc in the Pontides developed only in the beginning of the Late Cretaceous in the Turonian.

In the last ten years, Black Sea has been a target for hydrocarbon exploration (Şen, 2013). The main problem encountered along the Turkish sector of the Black Sea has been the poor porosity and permeability of the sandstone reservoirs. A northward source from the granitoids and gneisses of the East European Platform for the Lower Cretaceous sediments imply possible good reservoir sandstones within the Black Sea.

6. Conclusions

The Lower Cretaceous turbidites, called as the Çağlayan Formation, and associated shelf deposits crop out over an area of 400 km by 90 km and have a thickness of over two kilometers in the Central Pontides in northern Turkey. Here, we report detrital zircon ages from 1348 grains from 13 sandstone samples and REE abundances of detrital zircons of the Lower Cretaceous turbidites, the geochemistry of 242 detrital rutile grains from 4 sandstone samples and 1924 paleocurrent measurements from 96 stations.

1. Th/U ratios and REE values in the detrital zircons indicate that they were predominantly derived from magmatic protoliths either directly or indirectly through recycling.
2. Turbidites of the Lower Cretaceous Çağlayan Formation are bordered in the south by the Lower Cretaceous subduction-accretion units including eclogites and blueschists (Okay et al., 2006a, 2013; Aygül et al., 2015). The southern distal parts of the turbidites were also subducted and metamorphosed during the Early Cretaceous. Thus, The Çağlayan Formation occupies a fore-arc position immediately north of the Tethyan subduction zone.

3. The paleocurrent measurements, restored to their pre-rotational, pre-Late Cretaceous stage, indicate paleoflow direction towards ESE in the eastern part of the basin and predominantly paleoflow direction towards WSW in the western part of the basin (Fig. 6).
4. Detrital zircon ages show significant differences between the western, central and eastern part of the Çağlayan Basin (Figs. 9 and 10). In the eastern part the dominant zircon population is Archean and Paleoproterozoic. Rocks of these ages are unknown in the Pontides but crop out in the Ukrainian Shield north of the Black Sea. This together with ESE paleocurrents indicate that the eastern part of the basin was fed from the Ukrainian Shield (East European Platform). In the western part of the basin late Neoproterozoic and Carboniferous detrital zircons are predominant (Figs. 9 and 10), probably sourced from local sources in the Pontides. Zircon ages from the central part of the basin show a mixture of zircon age patterns of western and eastern parts of the Lower Cretaceous Basin.
5. Although the Çağlayan Formation occupied a fore-arc position during the Early Cretaceous, Lower Cretaceous detrital zircons are very rare in the sandstones (less than 1% of the total detrital zircon population). This, together with the absence of Lower Cretaceous intrusives in the Pontides, indicates that no magmatic arc developed during the Early Cretaceous, possibly due to flat subduction.
6. We envisage one or more rivers (Figs. 15a, b and 16) draining the East European Platform south to the Tethyan ocean and feeding the Çağlayan Basin during the Early Cretaceous. Local sources from uplifted fault blocks were important in the western part of the basin.
7. The close connection between the East European Platform and the Central Pontides, as shown by the detrital zircon and paleocurrent data, indicate that the Black Sea did not exist as a deep oceanic basin during the Early Cretaceous. It opened during the Late Cretaceous (Turonian-Santonian) along with the start of the arc volcanism.

8. Our data shows that a major part of the Çağlayan Basin is fed from the Archean–Paleoproterozoic granitic rocks of the Ukrainian Shield suggesting suitable sandstone reservoirs may exist in the Çağlayan Formation offshore.

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Supplementary material

Supplementary data associated with this article can be found, in the online version, at xxxx Appendix A. Paleocurrent measurement data sets and locality descriptions of the Lower Cretaceous Basin.

Appendix B. Paleocurrent measurement and sample preparation methods, and analytical techniques for U–Pb detrital zircon dating and rutile geochemistry.

Appendix C. Petrographic descriptions of the samples dated by U–Pb method and used for rutile geochemistry.

Appendix D. U–Pb isotopic ages of 13 samples from the detrital zircons of the Lower Cretaceous sandstones.

Appendix E. REE concentrations of the detrital zircons from the Lower Cretaceous sandstones.

Appendix F. Detrital rutile geochemistry of the Lower Cretaceous sandstones obtained by EMP.

References

- Akbayram, K., Okay, A.I., Satır, M., 2013. Early Cretaceous closure of the Intra-Pontide Ocean in western Pontides (northwestern Turkey). *Journal of Geodynamics* 65, 38–55.
- Altınır, D., Koçyiğit, A., Farinacci, A., Nicosia, U., Conti, M.A., 1991. Jurassic-Lower Cretaceous stratigraphy and paleogeographic evolution of the southern part of north-western Anatolia. *Geologica Romana* 28, 13–80.
- Aygül, M., Okay, A.I., Oberhänsli, R., Ziemann, M.A., 2015. Thermal structure of low–grade accreted Lower Cretaceous distal turbidites, the Central Pontides, Turkey: insights for tectonic thickening of an accretionary wedge. *Turkish Journal of Earth Sciences* 24, 461–474.
- Aygül, M., Okay, A.I., Oberhänsli, R., Sudo, M., 2016. Pre–collisional accretionary growth of the Southern Laurusian active margin, Central Pontides, Turkey. *Tectonophysics* 671, 218–234.
- Aysal, N., Ustaömer, T., Öngen, S., Keskin, M., Köksal, S., Peytcheva, I., Fanning, M., 2012. Origin of the Early-Middle Devonian magmatism in the Sakarya Zone, NW Turkey: Geochronology, geochemistry and isotope systematics. *Journal of Asian Earth Sciences* 45, 201–222.

- Baraboshkin, E.Y., Alekseev, A.S., Kopaevich, L.F., 2003. Cretaceous palaeogeography of the North-Eastern Peri-Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology* 196, 177–208.
- Belousova E.A., Griffin W.L., Pearson N.J., 1998. Trace element composition and cathodoluminescence properties of southern African kimberlitic zircons. *Mineralogical Magazine* 62, 355–366.
- Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., Fisher, N.J., 2002. Igneous zircon: Trace element composition as an indicator of source rock type. *Contributions to Mineralogy and Petrology* 143, 602–622.
- Bibikova, E.V., Bogdanova, S.V., Postnikov, A.V., Fedotova, A.A., Claesson, S., Kirnozova, T.I., Fugzan, M.M., Popova, L.P., 2015. The early crust of the Volgo-Uralian segment of the East European Craton: Isotope-geochronological zirconology of metasedimentary rocks of the Bolshecheremshanskaya Formation and their Sm-Nd model ages. *Stratigraphy and Geological Correlation* 23, 1–23.
- Bogdanova S.V., Bingen B., Gorbatshev R., Kheraskova T.N., Kozlov V.I., Puchkov V.N., Volozh Y. A., 2008. The East European Craton (Baltica) before and during the assembly of Rodinia. *Precambrian Research* 160, 23–45.
- Bogdanova, S.V., De Waele, B., Bibikova, E.V., Belousova, E.A., Postnikov, A.v., Fedotova, A.A., Popova, L.P., 2010. Volgo-Uralia: The first U–Pb, Lu–Hf, and Sm–Nd isotopic evidence of preserved Paleoproterozoic crust. *American Journal of Science* 310, 1345–1383.
- Carrigan, C.W., Mukasa, S.B., Haydoutov, I., Kolcheva, K., 2005. Age of Variscan magmatism from the Balkan sector of the orogen, central Bulgaria. *Lithos* 82, 125–147.
- Claesson, S., Bibikova, E., Bogdanova, S., Skobelev, V., 2006. Archean terranes, Paleoproterozoic reworking and accretion in the Ukrainian Shield, East-European Craton.

- In: Gee, D.G., Stephenson, R.A. (Eds.), *European Lithosphere Dynamics*. Geological Society of London, Memoir 32, 645–654.
- Chen, F., Siebel, W., Satır, M., Terzioğlu, N., Saka, K., 2002. Geochronology of the Karadere basement (NW Turkey) and implications for the geological evolution of the Istanbul Zone. *International Journal of Earth Sciences* 91, 469–481.
- Cloos, M., 1993. Lithospheric buoyancy and collisional orogenesis: subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. *Geological Society of America Bulletin* 105, 715–737.
- Dean, W.T., Monod, O., Rickards, R.B., Demir, O., Bultynck, P., 2000. Lower Palaeozoic stratigraphy and paleontology, Karadere-Zirze area, Pontus Mountains, northern Turkey. *Geological Magazine* 137, 555–582.
- Derman, A.S., 2002. Black Sea rift sequences. *Türkiye Petrol Jeologları Derneği Bülteni* 14, 36–65.
- Dickinson, W., Snyder, W., 1978. Plate tectonics of the Laramide orogeny. *Geological Society of America Memorial* 151, 355–366.
- Dokuz, A., 2011. A slab detachment and delamination model for the generation of Carboniferous high potassium I-type magmatism in the Eastern Pontides, NE Turkey: Köse composite pluton. *Gondwana Research* 19, 926–944.
- Dokuz, A., Karslı, O., Chen, B., Uysal, I., 2010. Sources and petrogenesis of Jurassic granitoids in the Yusufeli area, Northeastern Turkey: Implications for pre- and post-collisional lithospheric thinning of the eastern Pontides. *Tectonophysics* 480, 258–279.
- Fedo, C.M., Sircombe, K.N., Rainbird, R.H., 2003. Detrital zircon analysis of the sedimentary record. *Reviews in Mineralogy and Geochemistry* 53, 277–303.

- Finzel, E.S.; Ridgway, K.D., Trop, J.M., 2015. Provenance signature of changing plate boundary conditions along a convergent margin: Detrital Record of Spreading-Ridge and Flat-Slab Subduction Processes, Cenozoic Forearc Basins, Alaska. *Geosphere* 11, 823-849.
- Force, E.R., 1980. The provenance of rutile. *Journal of Sedimentary Petrology* 50, 485–488.
- Gehrels, G.E., Dickinson, W.R., Ross, G.M., Stewart, J.H., Howell, D.G., 1995. Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America. *Geology* 23, 831–834.
- Genç, S.C., Tüysüz, O., 2010. Tectonic setting of the Jurassic bimodal magmatism in the Sakarya Zone (Central and Western Pontides), Northern Turkey: A geochemical and isotopic approach. *Lithos* 118, 95–111.
- Görür, N., Tüysüz, O., Aykol, A., Sakıncı, M., Yiğitbaş, E., Akkök, R., 1993. Cretaceous red pelagic carbonates of northern Turkey: their place in the opening history of the Black Sea. *Eclogae Geologicae Helveticae* 86, 819–838.
- Görür, N., Monod, O., Okay, A.I., Şengör, A.M.C., Tüysüz, O., Yiğitbaş, E., Sakıncı, M., Akkök, R., 1997. Paleogeographic and tectonic position of the Carboniferous rocks of the western Pontides (Turkey) in the frame of the Variscan belt. *Bulletin de la Société Géologique de France* 168, 197–205.
- Gutscher, M.A., Spakman, W., Bijwaard, H., Engdahl, E., 2000. Geodynamics of flat subduction: seismicity and tomographic constraints from the Andean margin. *Tectonics* 19, 814–833.
- Hippolyte, J.-C., Müller, C., Kaymakcı, N., Sangu, E., 2010. Dating of the Black Sea Basin: New nannoplankton ages from its inverted margin in the Central Pontides (Turkey). In: Stephenson, R. A., Kaymakcı, N., Sosson, M., Starostenko, V., Bergerat, F. (Eds.),

- Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform. Geological Society of London, Special Publications 340, 113–136.
- Hoskin, P.W.O., Ireland, T.R., 2000. Rare earth element chemistry of zircon and its use as a provenance indicator. *Geology* 28, 627–630.
- Hoskin, P.W.O. and Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis. *Reviews in Mineralogy and Geochemistry*, 53, 27–62.
- Ingersoll, R., 1979. Evolution of the Late Cretaceous forearc basin, northern and central California. *Geological Society of America Bulletin*, 90, 813–826.
- Jacobson, C.E., Grove, M., Pedrick, J.N., Barth, A.P., Marsaglia, K.M., Gehrels, G., Nourse, J., 2011. Late Cretaceous-early Cenozoic tectonic evolution of the southern California margin inferred from provenance of trench and forearc sediments. *Geological Society of America Bulletin* 123, 485–506.
- Kandemir, R., Yılmaz, C., 2009. Lithostratigraphy, facies, and deposition environment of the lower Jurassic Ammonitico Rosso type sediments (ARTS) in the Gümüşhane area, NE Turkey: Implications for the opening of the northern branch of the Neo-Tethys Ocean. *Journal of Asian Earth Sciences* 34, 586–598.
- Karslıoğlu, Ö., Ustaömer, T., Roebtson, A.H.F., Peytcheva, I., 2012. Age and provenance of detrital zircons from a sandstone turbidite of the Triassic-Early Jurassic Küre Complex, Central Pontides. Abstracts, International Earth Science Colloquium on the Aegean Region, IAESCA–2012, p.57.
- Kaygusuz, A., Arslan, M., Wolfgang, S., Sipahi, F., İlbeyli, N., 2012. Geochronological evidence and tectonic significance of Carboniferous magmatism in the southwest Trabzon area, eastern Pontides. *Turkey International Geology Review* 54, 1776–1800.

- Kortyna, C., Donaghy, E., Trop, J. M., Idleman, B., 2014. Integrated provenance record of a forearc basin modified by slab-window magmatism: detrital- zircon geochronology and sandstone compositions of the Paleogene Arkose Ridge Formation, south-central Alaska. *Basin Research* 26, 436–460.
- Kylander-Clark, A.R.C., Hacker B. R., Cottle, J. M., 2013. Laser-Ablation Split-Stream ICP Petrochronology. *Chemical Geology* 345, 99-112.
- Linnemann, U., Ouzegane, K., Drareni, A., Hofmann, M., Becker, S., Gärtner, A., Sagawe, A., 2011. Sands of West Gondwana: An archive of secular magmatism and plate interactions— A case study from the Cambro–Ordovician section of the Tassili Ouan Ahaggar (Algerian Sahara) using U–Pb–LA–ICP–MS detrital zircon ages. *Lithos* 123, 188–203.
- Masse, J.-P., Tüysüz, O., Fenerci-Masse, M., Özer, S., Sarı, B., 2009. Stratigraphic organisation, spatial distribution, paleoenvironmental reconstruction, and demise of Lower Cretaceous (Barremian–lower Aptian) carbonate platforms of the Western Pontides (Black Sea region, Turkey). *Cretaceous Research* 30, 1170–1180.
- Mattern, F., 2005. Ancient sand-rich submarine fans, depositional systems, models, identification, and analysis. *Earth-Science Reviews* 70, 167–202.
- Mayringer, F., Treloar, P.J., Gerdes, A., Finger, F., Shengelia, D., 2011. New age data from the Dzirula Massif, Georgia: Implications for the evolution of the Caucasian Variscides. *American Journal of Science* 311, 404–441.
- McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. *Chemical Geology* 120, 223–253.
- McGeary, S., Nur, A., Ben-Avraham, Z., 1985. Spacial gaps in arc volcanism: the effect of collision or subduction of oceanic plateaus. *Tectonophysics* 119, 195–221.

- Meijers, M.J.M., Vrouwe, B., van Hinsbergen, D.J.J., Kupier, K.F., Wijbrans, J., Davies, G.R., Stephenson, R.A., Kaymakci, N., Matenco, L., Saintot, A., 2010a. Jurassic arc volcanism on Crimea (Ukraine): Implications for the paleo-subduction zone configuration of the Black Sea region. *Lithos* 119, 412–426.
- Meijers, M.J.M., Kaymakci, N., van Hinsbergen, D.J.J., Langereis, C.G., Stephenson, R.A., Hippolyte, J.-C., 2010b. Late Cretaceous to Paleocene oroclinal bending in the central Pontides (Turkey). *Tectonics* 29, TC4016, doi: 10.1029/2009TC002620.
- Meinhold, G., 2010. Rutile and its applications in earth sciences. *Earth-Science Reviews* 102, 1–28.
- Meinhold, G., Anders, B., Kostopoulos, D., Reischmann, T., 2008. Rutile chemistry and thermometry as provenance indicator: An example from Chios Island, Greece. *Sedimentary Geology* 203, 98–111.
- Meinhold, G., Morton, A.C., Avigad, D., 2013. New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U–Pb ages. *Gondwana Research* 23, 661–665.
- Morton, A.C., Hallsworth, C.R., 1999. Processes controlling the composition of heavy mineral assemblages in sandstones. *Sedimentary Geology* 124, 3–29.
- Neubauer, F., 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. *Tectonophysics* 352, 87–103.
- Nikishin, A.M., Okay, A., Tüysüz, O., Demirer, A., Wannier, M., Amelin, N., Petrov, E., 2015a. The Black Sea basins structure and history: New model based on new deep penetration regional seismic data. Part 2: Tectonic history and paleogeography. *Marine and Petroleum Geology* 59, 656–670.

- Nikishin, A.M., Wannier, M., Alekseev, A.S., Almendinger, O.A., Fokin, P.A., Gabdullin, R.R., Khudoley, A.K., Kopaevich, L.F., Mityukov, A.V., Petrov, E.I., Rubtsova, E.V., 2015b. Mesozoic to recent geological history of southern Crimea and the Eastern Black Sea region. In Sosson, M., Stephenson, R.A., Adamia, S.A. (Eds.), Tectonic Evolution of the Eastern Black Sea and Caucasus. Geological Society of London, Special Publications 428, doi:10.1144/SP428.1
- Nzegge, O.M., 2008. Petrogenesis and geochronology of the Deliklitaş, Sivrikaya and Devrekani granitoids and basement, Kastamonu belt–Central Pontides (NW Turkey): Evidence for Late Palaeozoic–Mesozoic plutonism and geodynamic interpretation. PhD thesis, University of Tübingen, 167 pp.
- Nzegge, O.M., Satır, M., Siebel, W., Taubald, H., 2006. Geochemical and isotopic constraints on the genesis of the Late Palaeozoic Deliklitaş, and Sivrikaya granites from the Kastamonu granitoid belt (Central Pontides, Turkey). Neues Jahrbuch für Mineralogie Abhandlungen 183, 27–40.
- Okay, A.I., 1996. Granulite facies gneisses from the Pülür region, Eastern Pontides. Turkish Journal of Earth Sciences 5, 55–61.
- Okay, A.I., Göncüoğlu, M.C., 2004. Karakaya Complex: a review of data and concepts. Turkish Journal of Earth Sciences 13, 77–95.
- Okay, A.I., Monié, P., 1997. Early Mesozoic subduction in the Eastern Mediterranean: Evidence from Triassic eclogite in the northwest Turkey. Geology 25, 595–8.
- Okay, A.I., Nikishin, A.M., 2015. Tectonic evolution of the southern margin of Laurasia in the Black Sea region. International Geology Review 57, 1051–1076.

- Okay, A.I., Şahintürk, Ö., 1997. Geology of the Eastern Pontides. In: Robinson, A.G. (Ed.), Regional and petroleum geology of the Black Sea and surrounding region. AAPG Memoir, 68, 291–311.
- Okay, A.I., Tüysüz, O., 1999. Tethyan sutures of northern Turkey. In Durand B., Jolivet L., Horváth F., Séranne M. (Eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. Geological Society of London, Special Publications 156, 475–515.
- Okay, A.I., Satır, M., Maluski, H., Siyako, M., Monié, P., Metzger, R., Akyüz, S., 1996. Paleo- and Neo-Tethyan events in northwest Turkey: Geological and geochronological constraints. In: Yin, A., Harrison, M. (Eds.), Tectonics of Asia. Cambridge University Press, pp. 420–441.
- Okay, A.I., Satır, M., Tüysüz, O., Akyüz, S., Chen, F., 2001. The tectonics of the Strandja Massif: Variscan and mid-Mesozoic deformation and metamorphism in the northern Aegean. International Journal of Earth Sciences 90, 217–233.
- Okay, A.I., Monod, O., Monié, P., 2002. Triassic blueschists and eclogites from northwest Turkey: Vestiges of the Paleo-Tethyan subduction. Lithos 64, 155–78.
- Okay, A.I., Tüysüz, O., Satır, M., Özkan-Altınır, S., Altınır, D., Sherlock, S., Eren, R.H., 2006a. Cretaceous and Triassic subduction-accretion, HP/LT metamorphism and continental growth in the Central Pontides, Turkey. Geological Society of America Bulletin 118, 1247–1269.
- Okay, A.I., Satır, M., Siebel, W., 2006b. Pre-Alpide orogenic events in the Eastern Mediterranean region, European Lithosphere Dynamics. . In: Gee, D., Stephenson, R. (Eds.), European Lithosphere Dynamics. Geological Society of London, Memoir, 32, 389–405.

- Okay, A.I., Bozkurt, E., Satır, M., Yiğitbaş, E., Crowley, Q.G. and Shang, C.K., 2008. Defining the southern margin of Avalonia in the Pontides: geochronological data from the Late Proterozoic and Ordovician granitoids from NW Turkey. *Tectonophysics*, 461, 252–264.
- Okay, A.I., Sunal, G., Sherlock, S., Altiner, D., Tüysüz, O., Kylander-Clark, A.R.C., Aygül, M., 2013. Early Cretaceous sedimentation and orogeny on the southern active margin of Eurasia; Central Pontides, Turkey. *Tectonics* 32, 1247–1271.
- Okay, A.I., Sunal, G., Tüysüz, O., Sherlock, S., Keskin, M., Kylander-Clark, A.R.C., 2014. Low-pressure–high-temperature metamorphism during extension in a Jurassic magmatic arc, Central Pontides, Turkey. *Journal of Metamorphic Geology* 32, 49–69.
- Okay, N., Zack, T., Okay A.I., Barth, M., 2010. Sinistral transport along the Trans-European Suture Zone: detrital zircon–rutile geochronology and sandstone petrography from the Carboniferous flysch of the Pontides. *Geological Magazine* 148, 380–403.
- Özgül, N., 2012. Stratigraphy and some structural features of the Istanbul Palaeozoic. *Turkish Journal of Earth Sciences* 21, 817–866.
- Reading, H.G., Richards, M., 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *American Association of Petroleum Geology Bulletin* 78, 792–822.
- Rollinson, H.R., 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman, Scientific and Technical, Harlow, 352 pp.
- Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism. *Chemical Geology* 184, 123–138.
- Rupke, N.A., 1978. Deep clastic seas. In: Reading, H.G., (Ed.), *Sedimentary Environments and Facies*. 1st edition, Blackwell, Oxford, pp. 372–415.

- Safonova, I., Maruyama, S., Hirata, T., Kon, Y., Rino, S., 2010. LA ICP MS U–Pb ages of detrital zircons from Russia largest rivers: Implications for major granitoid events in Eurasia and global episodes of supercontinent formation. *Journal of Geodynamics* 50, 134–153.
- Shanmugam, G., Moiola, R.J., 1988. Submarine fans: characteristics, models, classification, and reservoir potential. *Earth-Science Reviews* 24, 383–428.
- Sharman, G.R., Graham, S.A., Grove, M., Kimnrough, D.L., Wright, J.E., 2015. Detrital zircon provenance of the Late Cretaceous–Eocene California forearc: Influence of Laramide low-angle subduction on sediment dispersal and paleogeography. *Geological Society of America Bulletin* 127, 38–60.
- Shchipansky, A.A., Bogdanova, S.V., 1996. The Sarmatian crustal segment: Precambrian correlation between the Voronezh Massif and the Ukrainian Shield across the Dniepr–Donets Aulacogen. *Tectonophysics* 268, 109–125.
- Somin, M., 2011. Pre-Jurassic basement of the Greater Caucasus: brief overview. *Turkish Journal of Earth Sciences* 20, 545–610.
- Sunal, G., 2013. Devonian magmatism in the western Sakarya Zone, Karacabey Region, NW Turkey. *Geodinamica Acta* 25, 183–201.
- Sunal, G., Natal'in, B., Satir, M., Toraman, E., 2006. Paleozoic magmatic events in the Strandja Masif, NW Turkey. *Geodinamica Acta* 19, 283–300.
- Sunal, G., Satir, M., Natal'in, B.A., Toraman, E., 2008. Paleotectonic position of the Strandja Massif and surrounding continental blocks based on zircon Pb–Pb age studies. *International Geology Review* 50, 519–45.
- Şen, Ş., 2013. New evidences for the formation of and for petroleum exploration in the fold-thrust zones of the central Black Sea Basin of Turkey. *American Association of Petroleum Geologist Bulletin* 97, 465–485.

- Şengör, A. M. C., Yılmaz, Y., 1981. Tethyan evolution of Turkey: a plate tectonic approach. *Tectonophysics* 75, 181–241.
- Tomkins, H., S., Powell, R., Ellis, D. J., 2007. The pressure dependence of the zirconium-in-rutile thermometer. *Journal of Metamorphic Geology* 25, 703–713.
- Topuz, G., Altherr, R., Kalt, A., Satır, M., Werner, O., Schwarz, W.H., 2004. Aluminous granulites from the Pulur complex, NE Turkey: a case of partial melting, efficient melt extraction and crystallization. *Lithos* 72, 183–207.
- Topuz, G., Altherr, R., Schwarz, W.H., Dokuz, A., Meyer, H.P., 2007. Variscan amphibolite facies metamorphic rocks from the Kurtoğlu metamorphic complex (Gümüşhane area, Eastern Pontides, Turkey). *International Journal of Earth Sciences*. 96, 861–873.
- Topuz, G., Altherr, R., Siebel, W., Schwarz, W.H., Zack, T., Hasözbek, A., Barth, M., Satır, M., Şen, C., 2010. Carboniferous high-potassium I-type granitoid magmatism in the Eastern Pontides: the Gümüşhane pluton (NE Turkey). *Lithos* 116, 92–110.
- Triebold, S., von Eynatten, H., Luvizotto, G.L., Zack, T., 2007. Deducing source rock lithology from detrital rutile geochemistry: an example from the Erzgebirge, Germany. *Chemical Geology* 244, 421–436.
- Triebold, S., Luvizotto, G., Tolosana-Delgado, R., Zack, T., von Eynatten, H., 2011. Discrimination of TiO₂ polymorphs in sedimentary and metamorphic rocks. *Contributions to Mineralogy and Petrology* 161, 581–596.
- Triebold, S., von Eynatten, H., Zack, T., 2012. A recipe for the use of rutile in sedimentary provenance analysis. *Sedimentary Geology* 282, 268–275.
- Tüysüz, O., 1999. Geology of the Cretaceous sedimentary basins of the Western Pontides. *Geological Journal*, 34, 75–93.

- Tüysüz O., Aksay A., Yiğitbaş, E., 2004. Stratigraphic Nomenclature of the Western Black Sea Region. General Directorate of Mineral Research and Exploration, Committee of Stratigraphy, Lithostratigraphy Units Serie I, Ankara [in Turkish].
- Ustaömer, P.A., Rogers, G., 1999. The Bolu Massif: remnant of a pre-Early Ordovician active margin in the west Pontides, northern Turkey. *Geological Magazine* 136, 579–592.
- Ustaömer, P.A., Mundil, R., Renne, P.R., 2005. U/Pb and Pb/Pb zircon ages for arc-related intrusions of the Bolu Massif (W Pontides NW Turkey): evidence for Late Precambrian (Cadomian) age. *Terra Nova* 17, 215–223.
- Ustaömer, P.A., Ustaömer, T., Gerdes, A., Zulauf, G., 2011. Detrital zircon ages from a lower Ordovician quartzite of the İstanbul exotic terrane (NW Turkey): Evidence for Amazonian affinity. *International Journal of Earth Sciences* 100, 23–41.
- Ustaömer, P.A., Ustaömer, T., Robertson, A.H.F., 2012. Ion probe U–Pb dating of the central Sakarya basement: A peri-Gondwana terrane intruded by late Lower Carboniferous subduction/collision-related granitic rocks. *Turkish Journal of Earth Sciences* 21, 905–932.
- Ustaömer, T., Robertson, A.H.F., 1994. Late Palaeozoic marginal basin and subduction-accretion: The Paleotethyan Küre Complex, Central Pontides, northern Turkey. *Journal of the Geological Society of London* 151, 291–305.
- Ustaömer, T., Robertson, A.H.F., Ustaömer, P.A., Gerdes, A., Peytcheva, I., 2012. Constraints on Variscan and Cimmerian magmatism and metamorphism in the Pontides (Yusufeli–Artvin area), NE Turkey from U–Pb dating and granite geochemistry. In: Robertson, A.H.F., Parlak, O., Ünlügenç, U.C., (Eds.), *Geological development of Anatolia and the easternmost Mediterranean region* Geological Society of London, Special Publications, 372, 49–74.

- Ustaömer, T., Ustaömer, P.A., Robertson, A.H.F., Gerdes, A., 2016. Implications of U–Pb and Lu–Hf isotopic analysis of detrital zircons for the depositional age, provenance and tectonic setting of the Permian–Triassic Palaeotethyan Karakaya Complex, NW Turkey. *International Journal of Earth Sciences* 105, 7–38.
- van Hunen, J., van den Berg, A.P., Vlaar, N.J., 2002. On the role of subducting oceanic plateaus in the development of shallow flat subduction. *Tectonophysics* 352, 317–333.
- Varol, B. and Akman, Ü., 1988. Facies properties of the Barremian - ?Aptian carbonates and their characteristic Dascyladecean algae (east of Amasra, Zonguldak, Turkey). *METU Journal of Pure and Applied Sciences*, 21, 307-319.
- Vavra, G., Schmid, R., Gebauer, D., 1999. Internal morphology, habit and U–Th–Pb microanalysis of amphibolite-to granulite facies zircons: geochronology of the Ivrea Zone (Southern Alps). *Contributions to Mineralogy and Petrology* 134, 380–404.
- Wang, C.Y., Campbell, I.H., Stepanov, A. S., Allen, C.M., Burtsev, I.N., 2011. Growth rate of the preserved continental crust: II. Constraints from Hf and O isotopes in detrital zircons from Greater Russian Rivers. *Geochimica et Cosmochimica Acta* 75, 1308–1345.
- Yılmaz, O., Boztuğ, D., 1986. Kastamonu granitoid belt of northern Turkey: First arc plutonism product related to the subduction of the Paleo-Tethys. *Geology* 14, 179–183.
- Yılmaz, İ.Ö., Altınır, D., 2007. Cyclostratigraphy and sequence boundaries of inner platform mixed carbonate-siliciclastic successions (Barremian-Aptian) (Zonguldak, NW Turkey). *Journal of Asian Earth Sciences* 30, 253–270.
- Yılmaz-Şahin, S., Güngör, Y., Aysal, N., Öngen, S., 2009. Istanca ve İstanbul zonları (KB Türkiye) içerisinde yüzeylenen granitoidlerin jeokimyası ve SHRIMP zirkon U–Pb yaşlandırması. In: 62. Türkiye Jeoloji Kurultayı Bildiri Özleri, 13-17 April 2009, Ankara, Turkey, pp. 598–599 (in Turkish).

- Yılmaz-Şahin, S., Aysal, N., Güngör, Y., Peytcheva, I., Neubauer, F., 2014. Geochemistry and U–Pb zircon geochronology of metagranites in Istranca (Strandja) Zone, NW Pontides Turkey: Implications for the geodynamic evolution of Cadomian Orogeny. *Gondwana Research* 26, 755–771.
- Yiğitbaş, E., Elmas, A., Yılmaz, Y., 1999. Pre-Cenozoic tectono-stratigraphic components of the western Pontides and their geological evolution. *Geological Journal* 34, 55–74.
- Yiğitbaş, E., Kerrich, E., Yılmaz, Y., Elmas, A., Xie, Q., 2004. Characteristics and geochemistry of Precambrian ophiolites and related volcanics from the Istanbul–Zonguldak Unit, Northwestern Anatolia Turkey: following the missing chain of the Precambrian South European Suture Zone to the east. *Precambrian Research* 132, 179–206.
- Zack, T., von Eynatten, H., Kronz, A., 2004. Rutile geochemistry and its potential use in quantitative provenance studies. *Sedimentary Geology* 171, 37–58.

Fig. Captions

Fig. 1. The main tectonic units of Black Sea region and depositional area of the Lower Cretaceous sediments. Abbreviations: CPS, Central Pontide Metamorphic Complex; EEC, East European Craton; E, Erzincan; Ç, Çankırı; WBS Fault, Western Black Sea Fault (modified from Okay et al., 2013).

Fig. 2. Outcrops of magmatic rocks with U–Pb zircon ages (modified from Okay and Nikishin, 2015). Isotopic ages of Jurassic magmatism are from Dokuz et al. (2010), Meijers et al. (2010a), Nzegge (2008), Okay et al. (2013, 2014); Carboniferous–Permian are from Dokuz (2011), Kaygusuz et al. (2012), Mayringer et al. (2011), Nzegge et al. (2006), Okay et al. (2001, 2006b, 2013, 2014), Somin (2011), Sunal et al. (2006), Topuz et al. (2004, 2010), Ustaömer et al. (2012), Ustaömer P. et al. (2012), Yılmaz-Şahin et al. (2009); Devonian

plutons are from Aysal et al. (2012), Okay et al. (1996, 2006b), Sunal (2013); Late Neoproterozoic–Ordovician plutons are from Akbayram et al. (2012), Chen et al. (2002), Mayringer et al. (2011), Okay et al. (2008), Ustaömer et al. (2012), Yılmaz-Şahin et al. (2009, 2014).

Fig. 3. Generalized stratigraphic section of the Central Pontides. For intrusion ages see Fig. 2.

Fig. 4. Field photographs of the Lower Cretaceous shelf and turbidite sequence of the Central Pontides. (a) Thickly bedded shelf carbonates interbedded with sandstone layers in the western part of the basin (Çengellidere). (b) The quartz arenites of shelf sediments near Zonguldak, (Kozlu). (c) Sandstone-shale alternations from turbidites (Boyabat-Gerze road). (d) General view of strongly folded distal parts of turbidites consisting mainly dark shales (~70%), in the southwestern part of the basin near Yenice, Karabük. (e) Flute casts indicating the paleocurrent direction to the southeast. (f) Mass flows in proximal parts of the turbidites in the western part, near Bartın. The clasts are mainly Late Jurassic–Early Cretaceous limestones.

Fig. 5. Paleocurrent directions in the Lower Cretaceous sediments in the Central Pontides. All measurements are corrected for tectonic tilting (for full data sets and methods see, Appendix A and B.1). Locations of samples for detrital zircon geochronology are also shown.

Fig. 6. Paleocurrents restored to their original directions after correction for oroclinal bending using the values in Meijers et al. (2010). The rotation angles for each locations are given in Appendix B.1.

Fig. 7. Histogram and pie chart showing the zircon age distribution of 13 samples from the Lower Cretaceous clastic rocks.

Fig. 8. Histogram with probability density curves and pie charts of 13 samples from the western, central and eastern parts of the basin. The violet probability density curve shows 90–110% concordant ages and the grey curve shows others.

Fig. 9. Combined histogram and probability density curves of the detrital zircon ages from western, central and eastern part of the Lower Cretaceous clastic rocks.

Fig. 10. Pie charts of the detrital zircon ages from the western, central and eastern parts of the Çağlayan Formation.

Fig. 11. Histogram showing the Phanerozoic and late Neoproterozoic zircon ages from all samples. The violet probability density curve shows 90–110% concordant ages and the grey curve shows others.

Fig. 12. Th/U ratio versus U–Pb ages of the detrital zircons from 13 samples. Discrimination lines are from Linnemann et al. (2011) and Rubatto (2002).

Fig. 13. Chondrite normalized REE patterns of detrital zircons from seven sandstone samples representing the western, central and eastern parts of the basin. Figures a₁–g₁ show detrital zircons are igneous in origin with steeply increasing LREE towards to HREE and with positive Ce and negative Eu anomaly (Hoskin and Schaltegger, 2003; Rubatto, 2002). Figures a₂–g₂ show metamorphic zircons (lines in red, zircons with Th/U ratio <0.08, some of them show subsolidus growth with garnet with flat or depleted HREE pattern) and zircons from mafic rocks (blue lines) with depletion in HREE and Th/U ratios > 0.1. Chondrite values are from McDonough and Sun, (1995).

Fig. 14. Combined histogram and pie charts showing detrital rutile source lithology and crystallization temperatures of four sandstone samples representing western, central and eastern parts of the Lower Cretaceous Basin. Source lithology discriminations of detrital

rutiles based on Nb and Cr contents according to Triebold et al. (2011, 2012). Zr in rutile thermometry of Tomkins et al. (2007) is used for temperature calculations.

Fig. 15. Paleographic maps of the southern active margin of Eurasia for Barremian–Aptian interval; a) more than one river feeding the basin, b) one major river feeding the basin an alternative model.

Fig. 16. Block diagram showing the tectonic setting of the Çağlayan Basin during the Early Cretaceous.

Table 1. Sample locations for U-Pb detrital zircon geochronology and detrital rutile geochemistry.

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Figure1

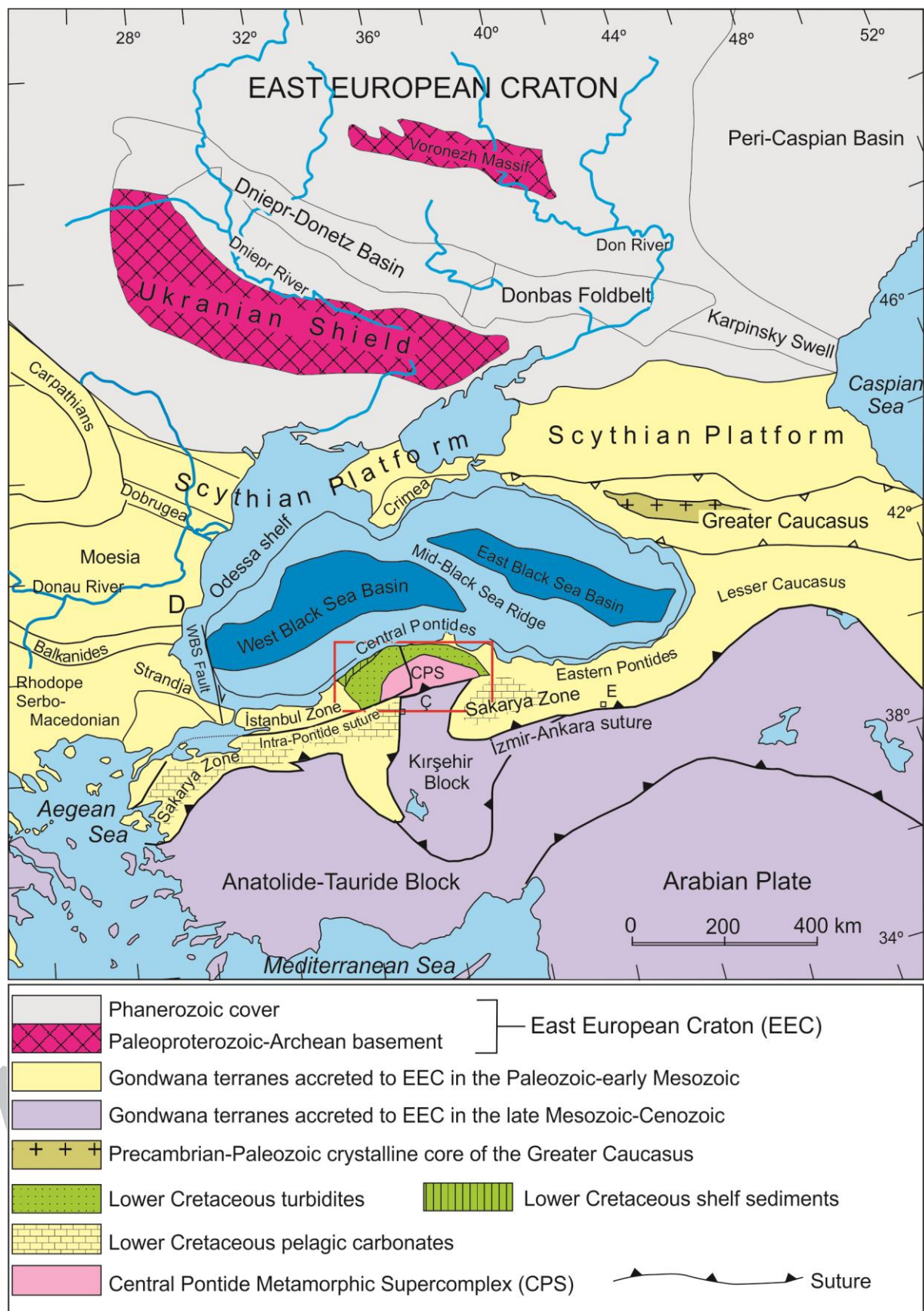


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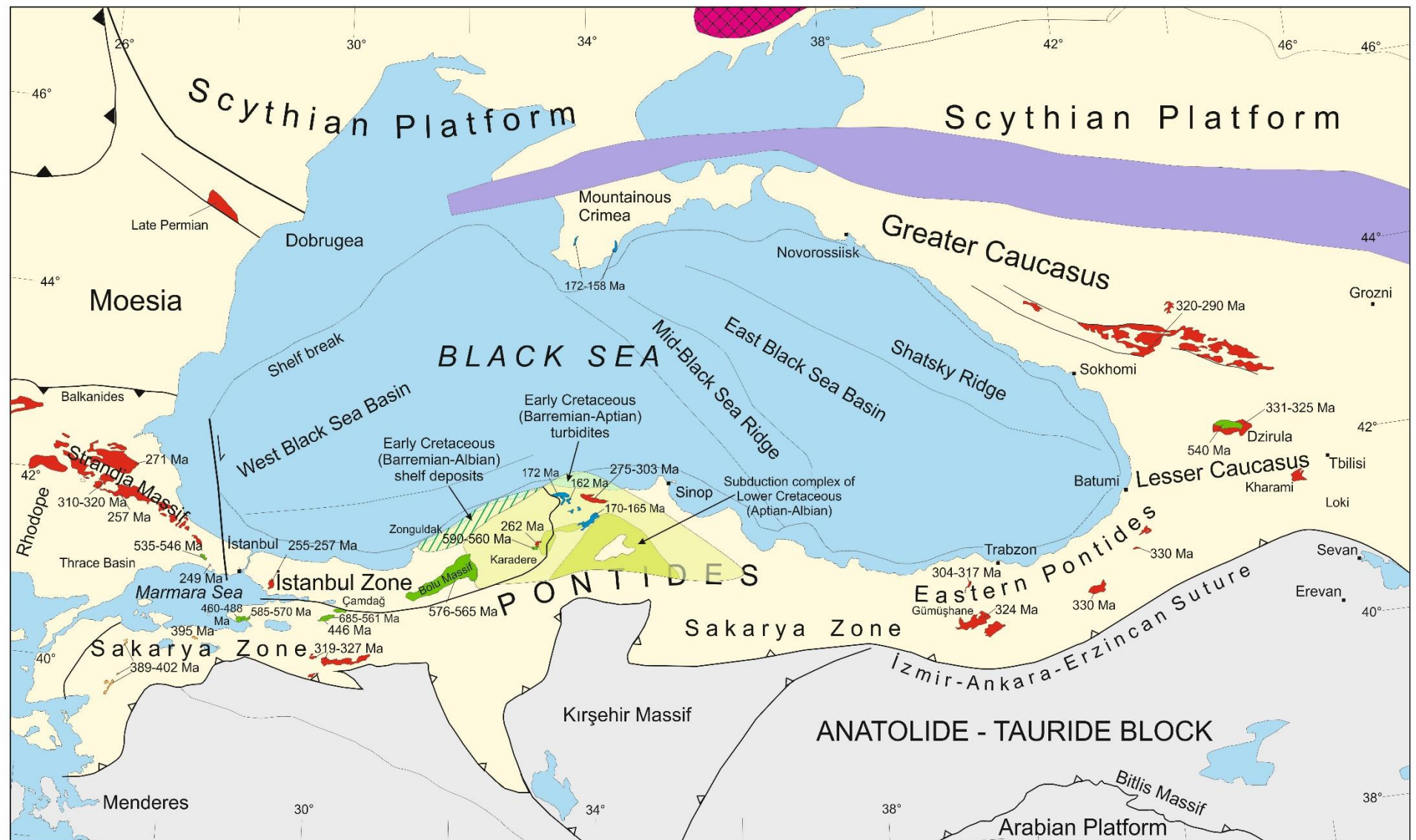


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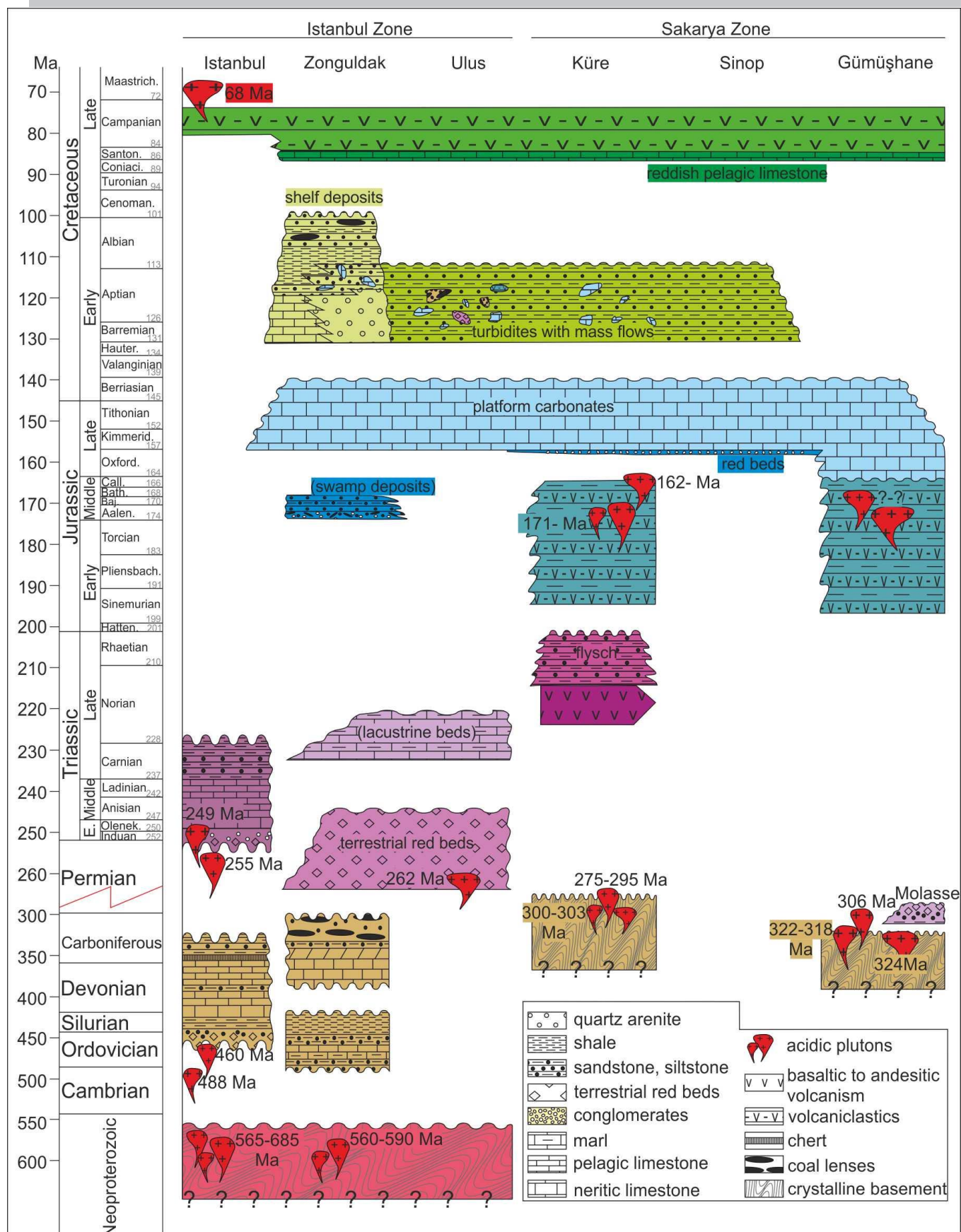


Figure4

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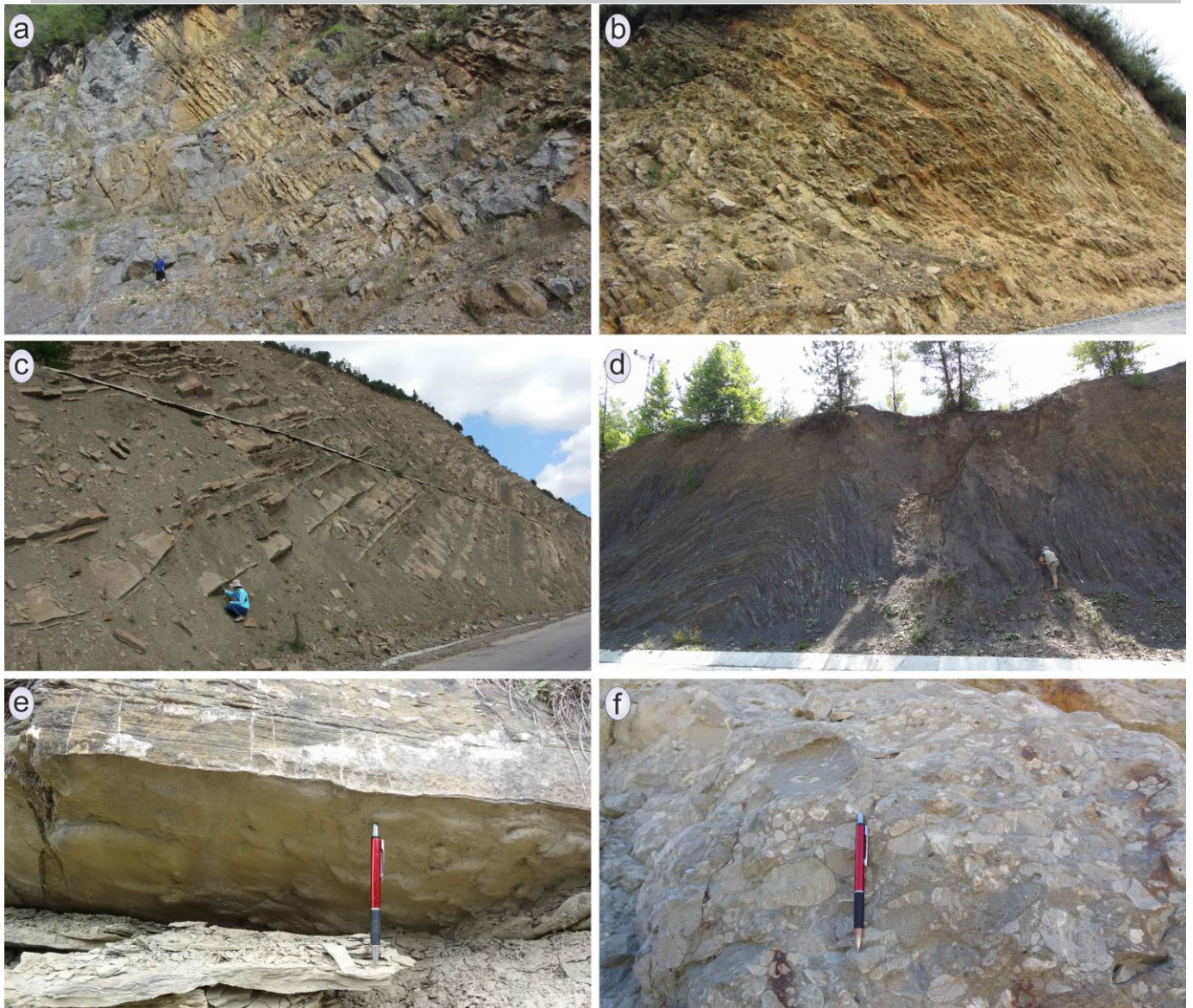


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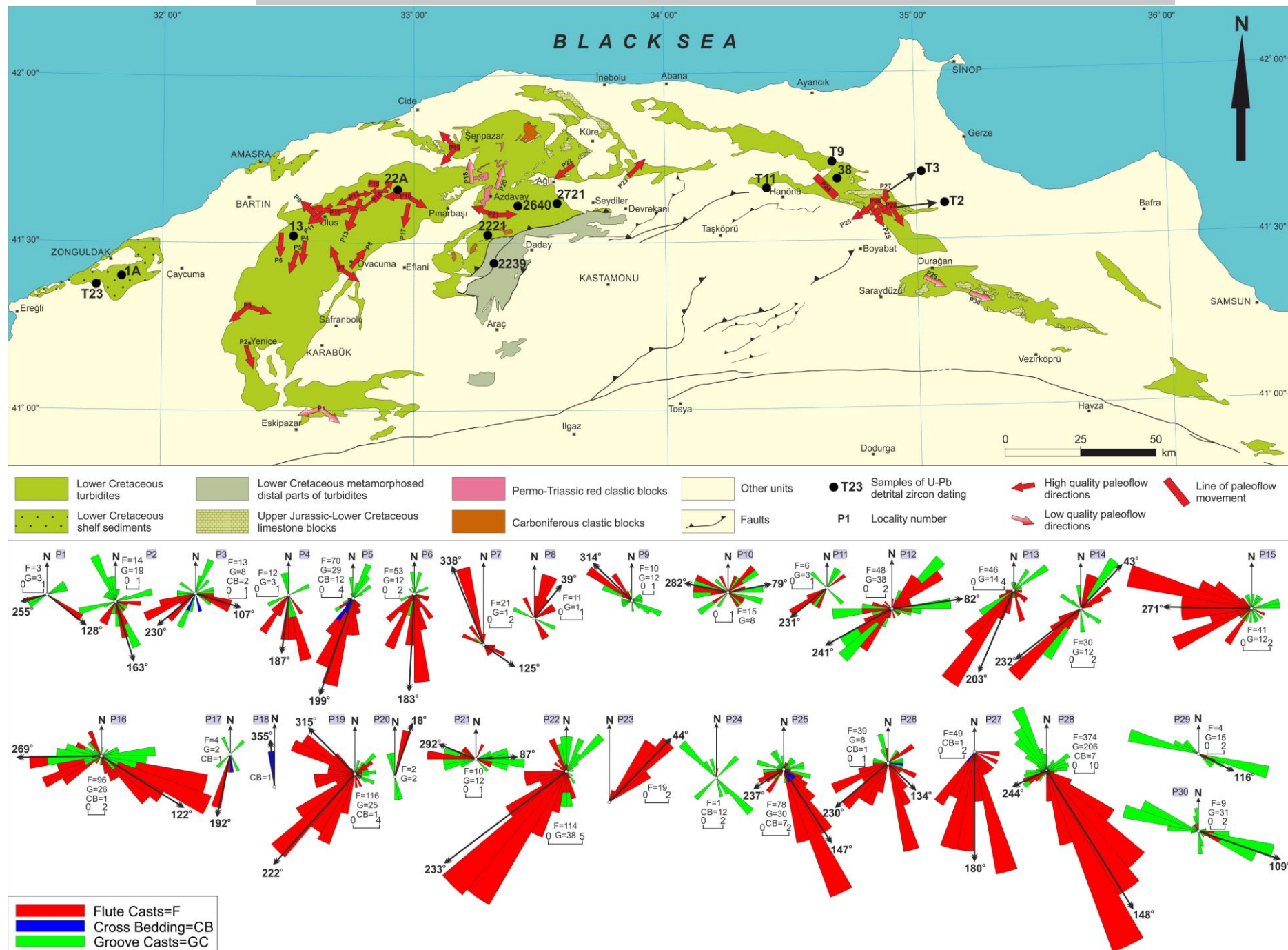


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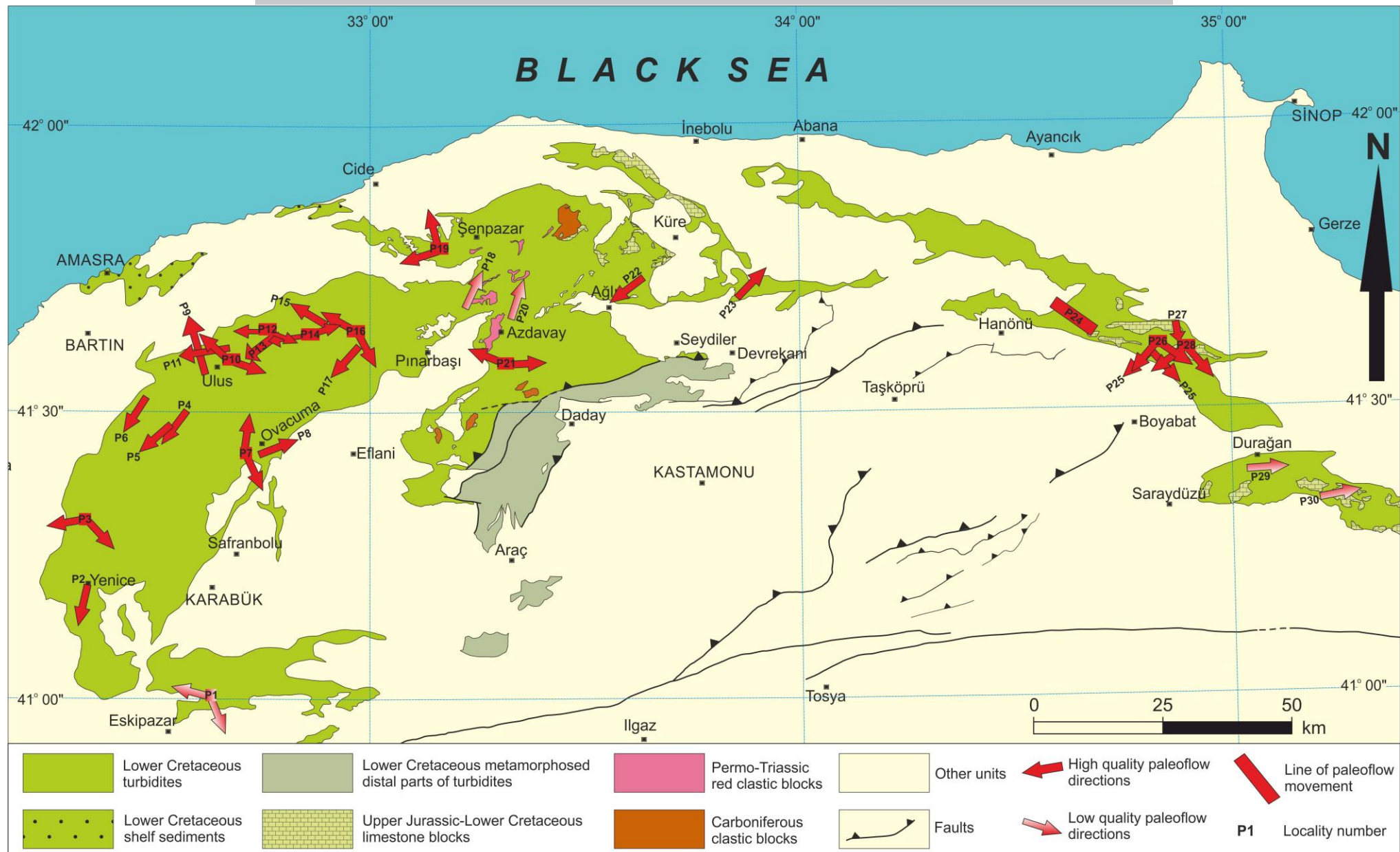


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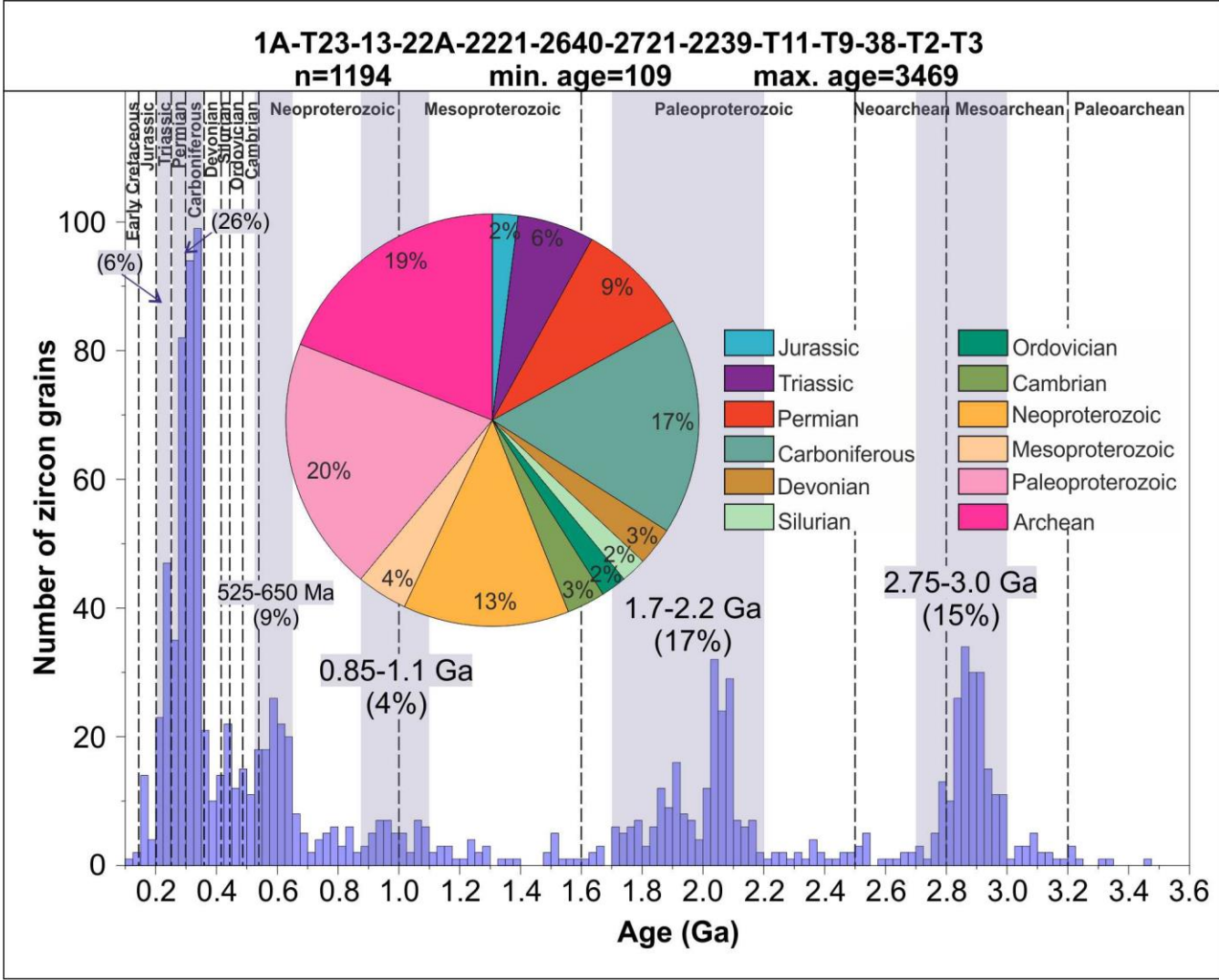


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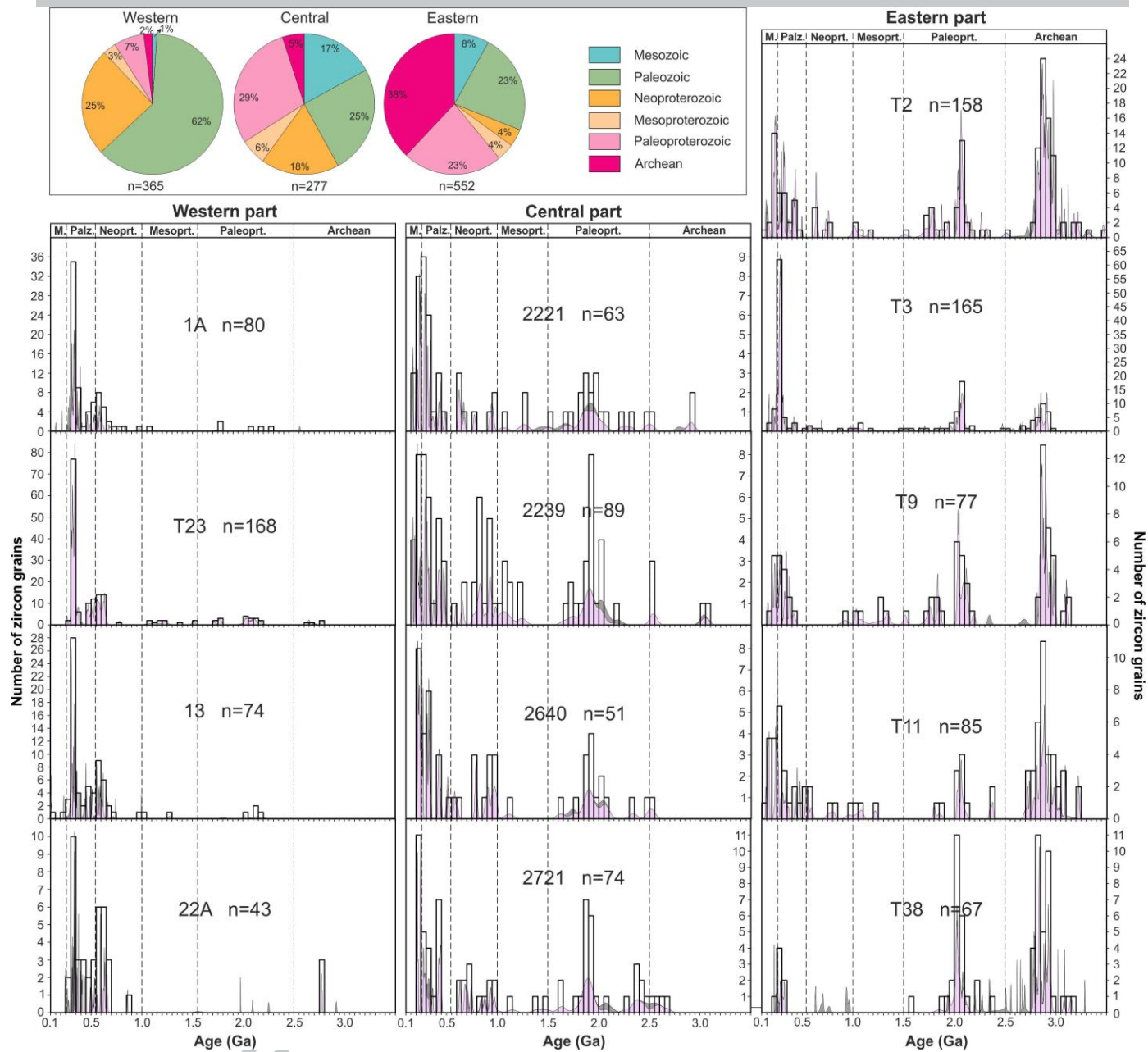


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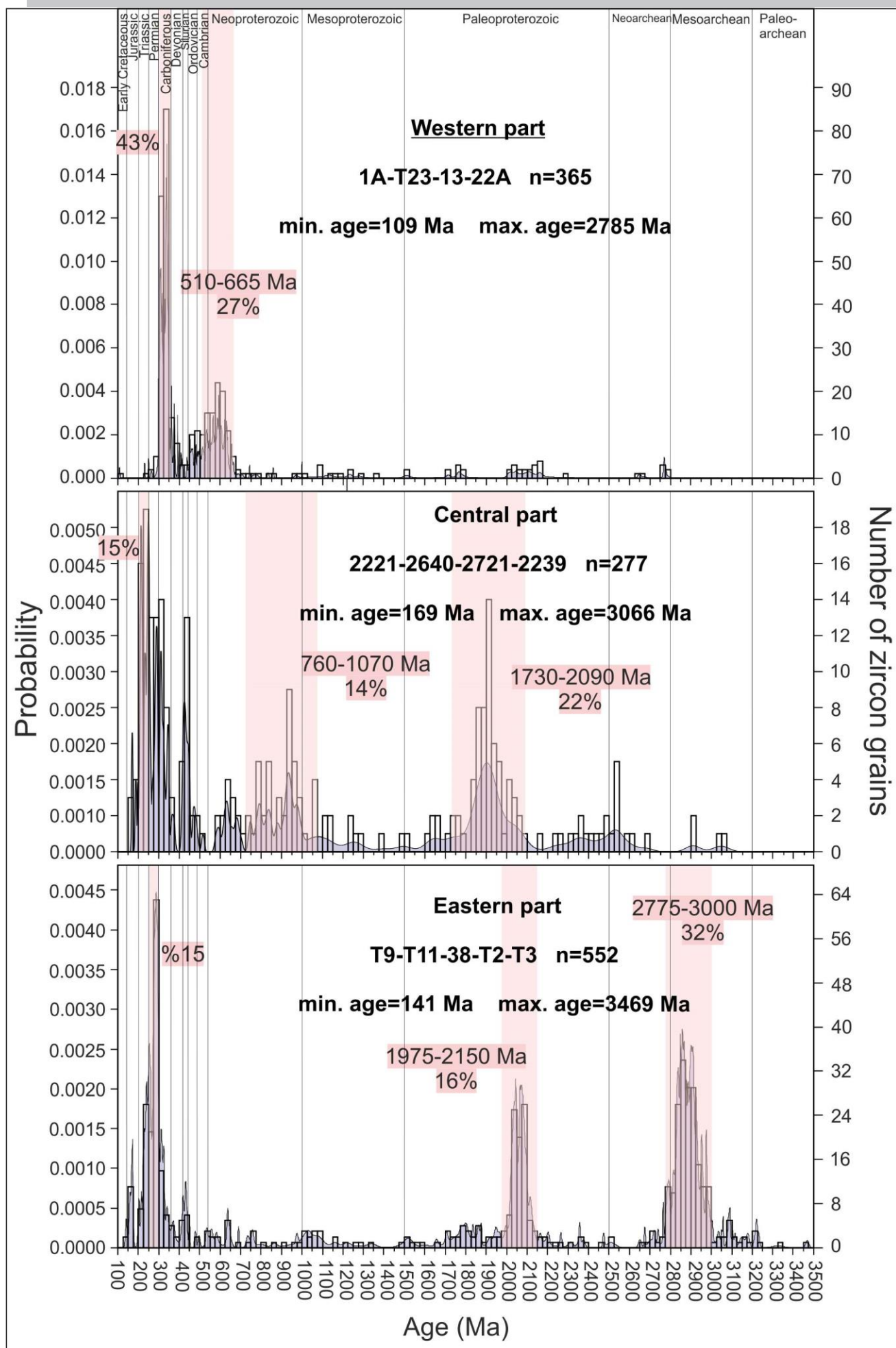
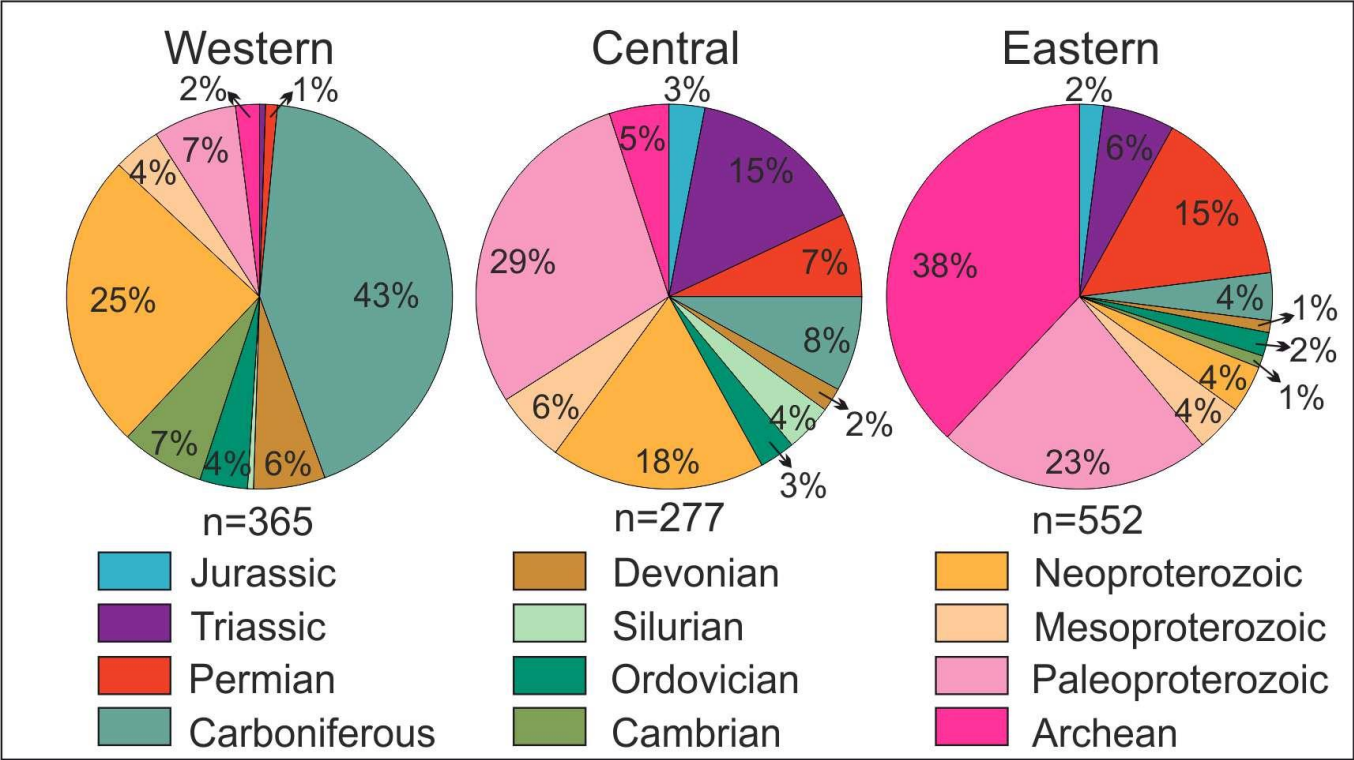
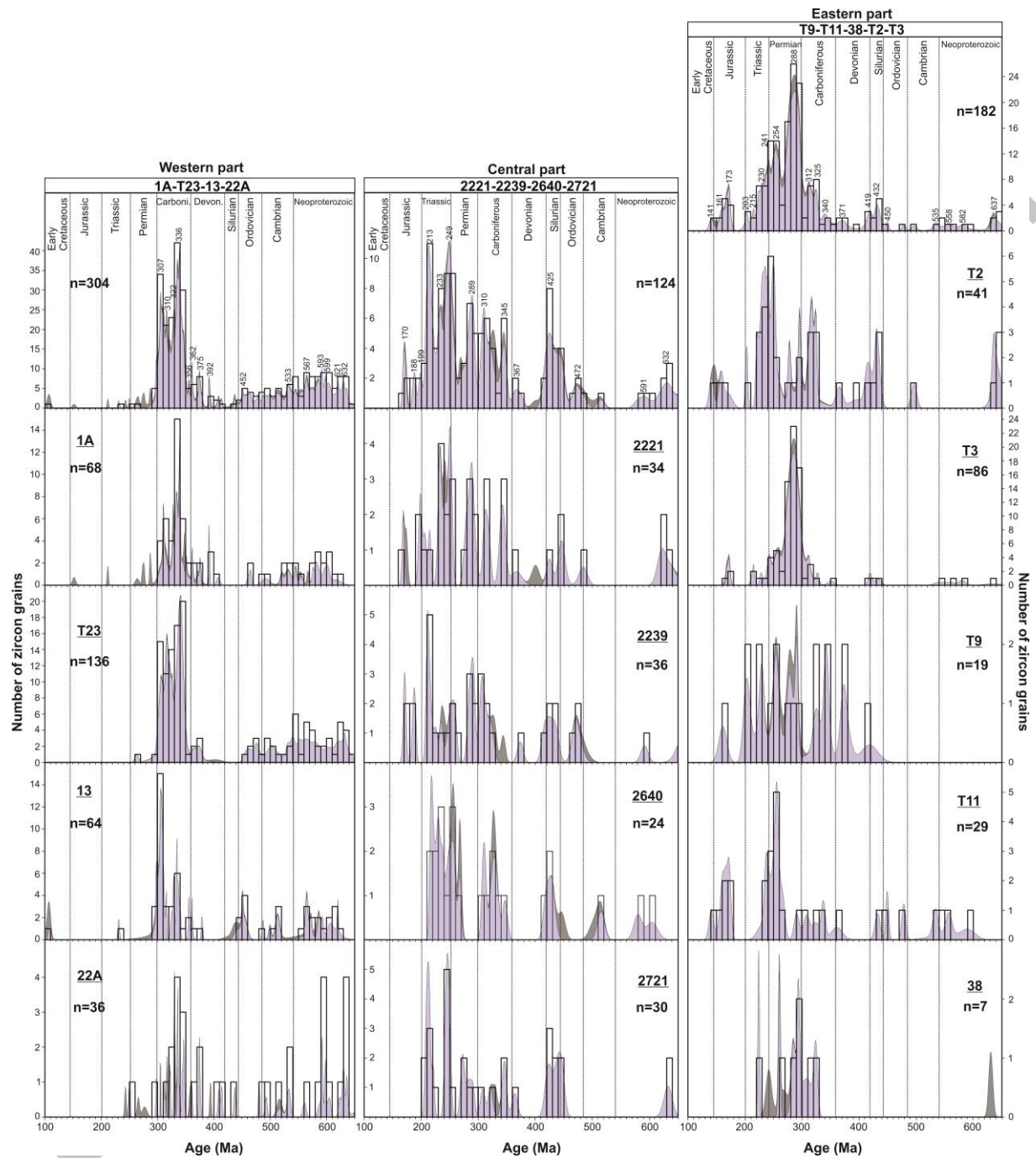


Figure10





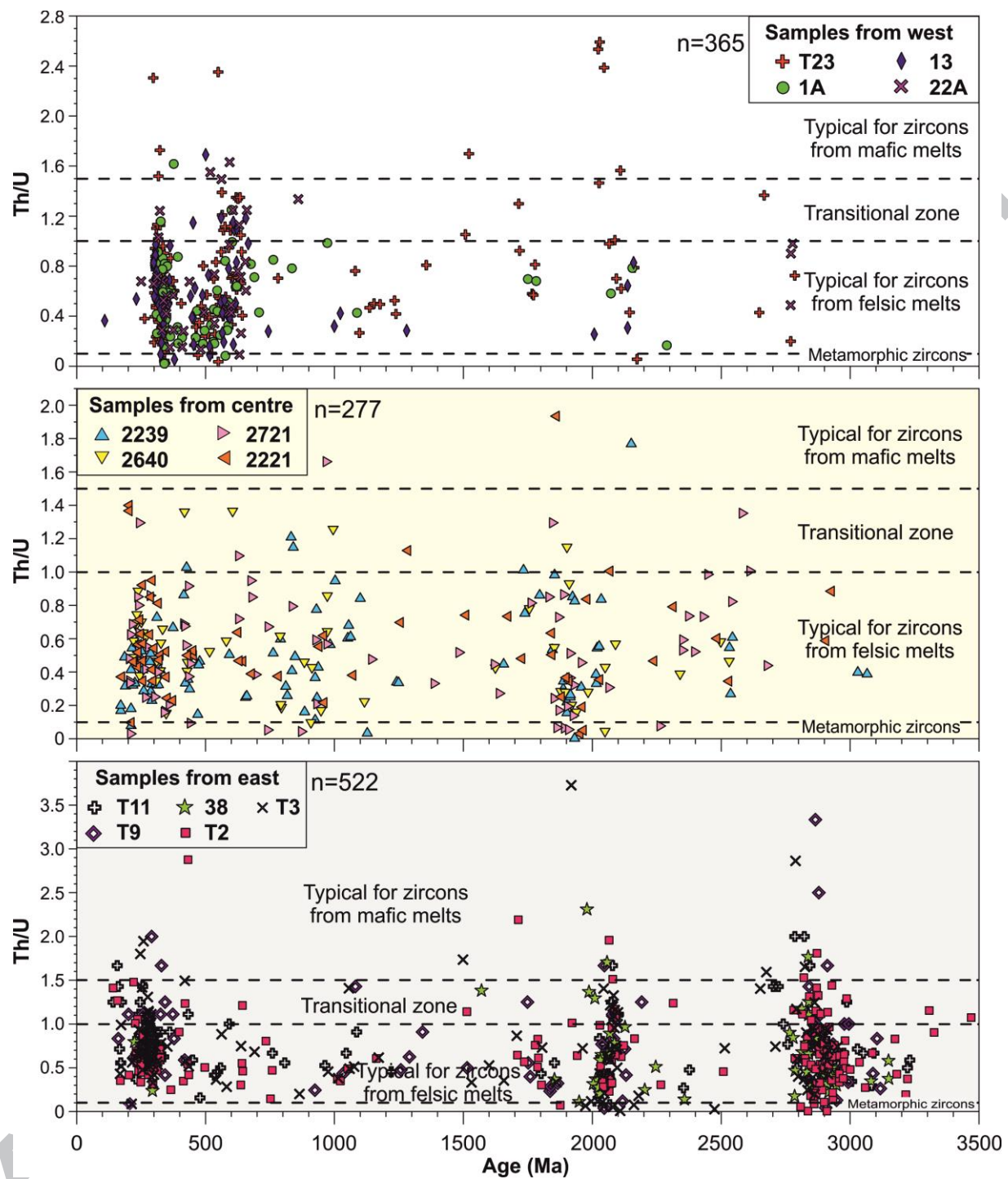


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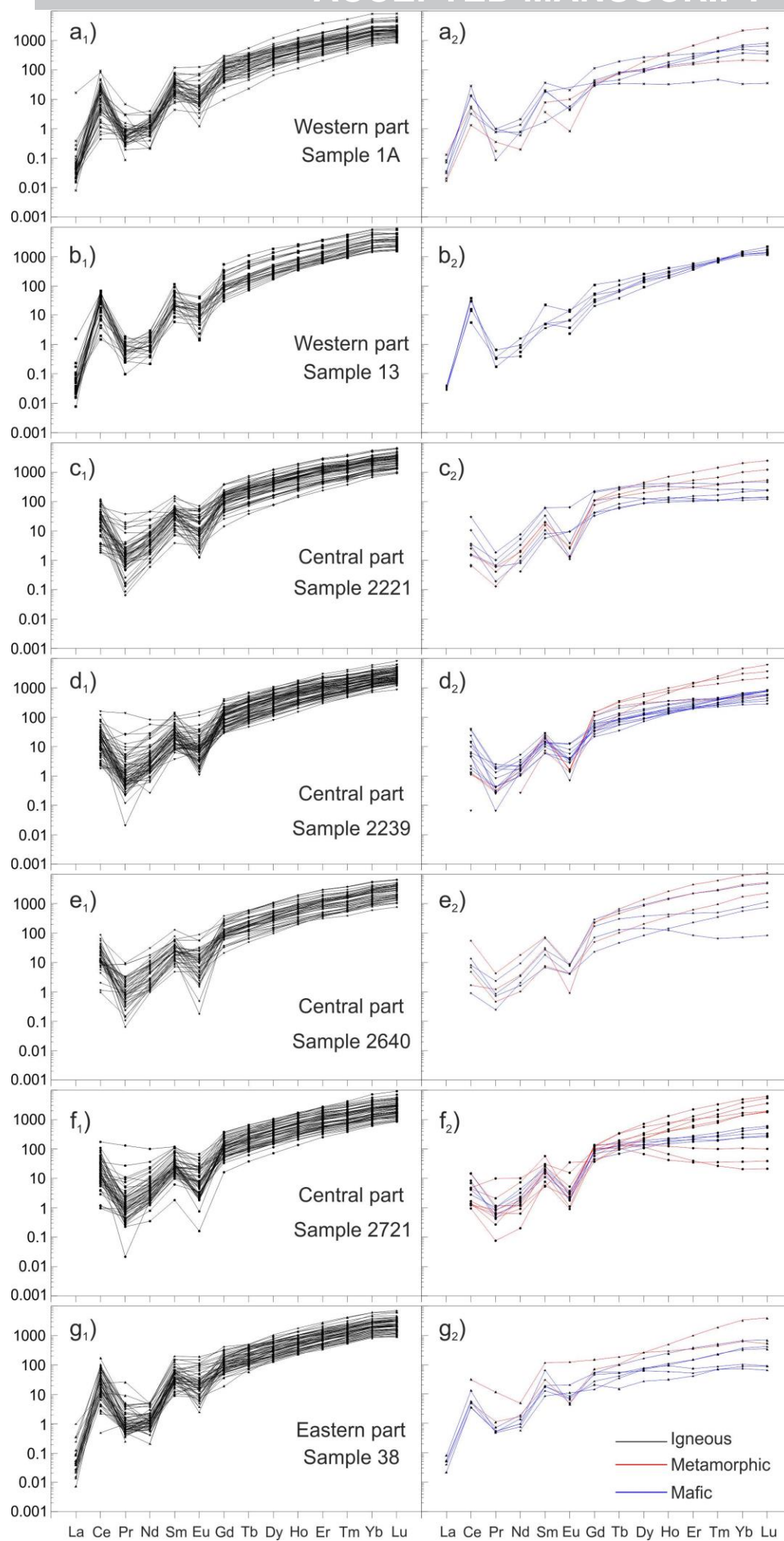


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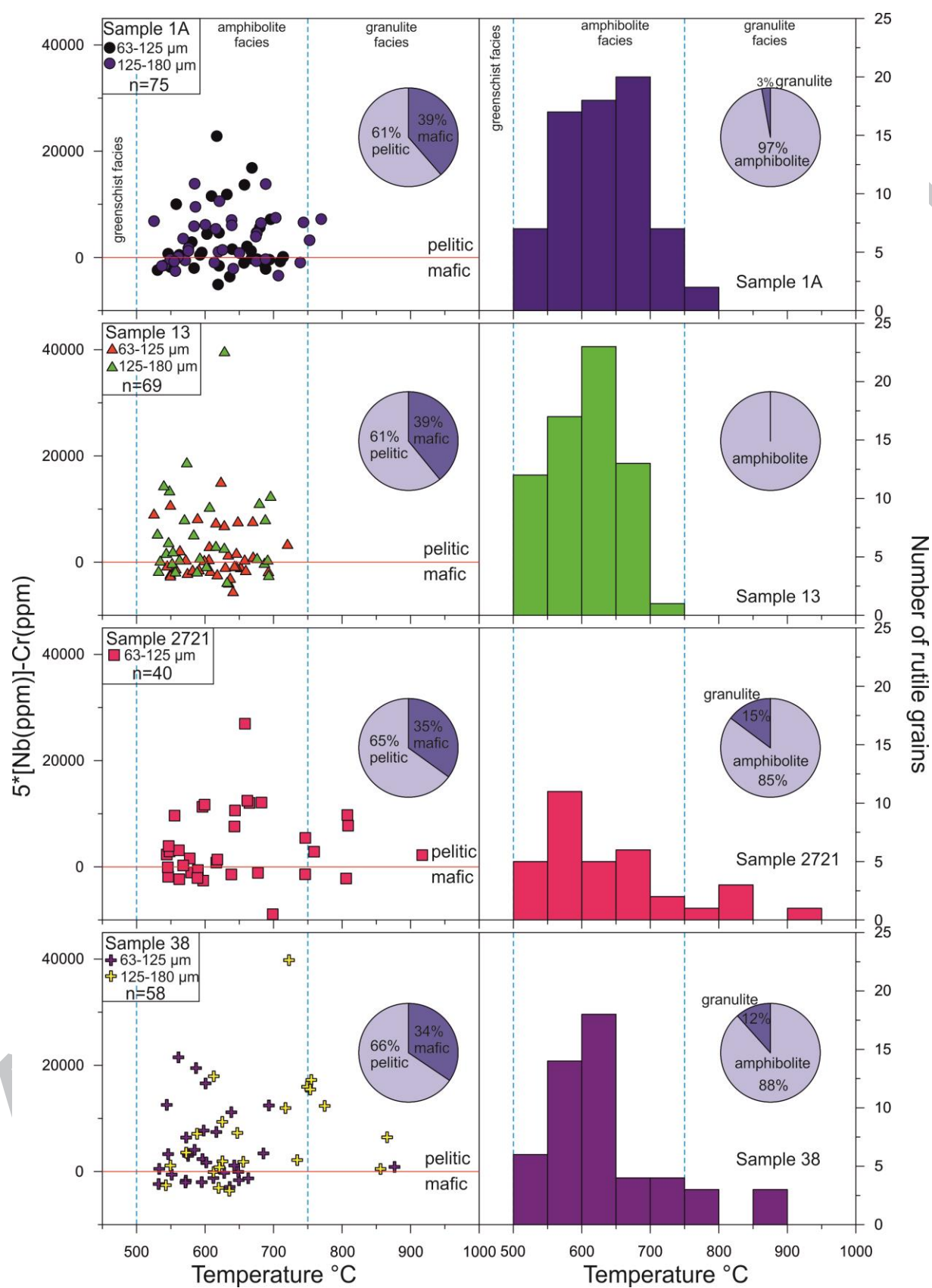


Figure15

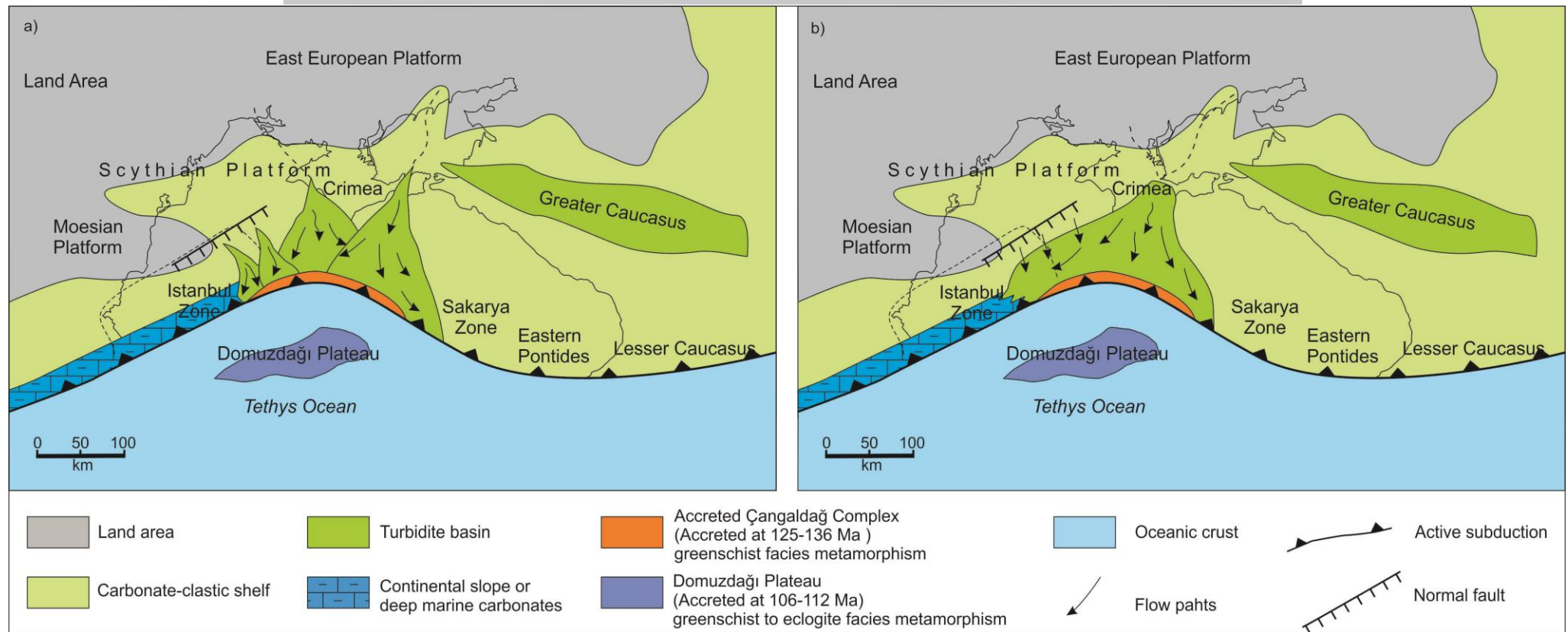
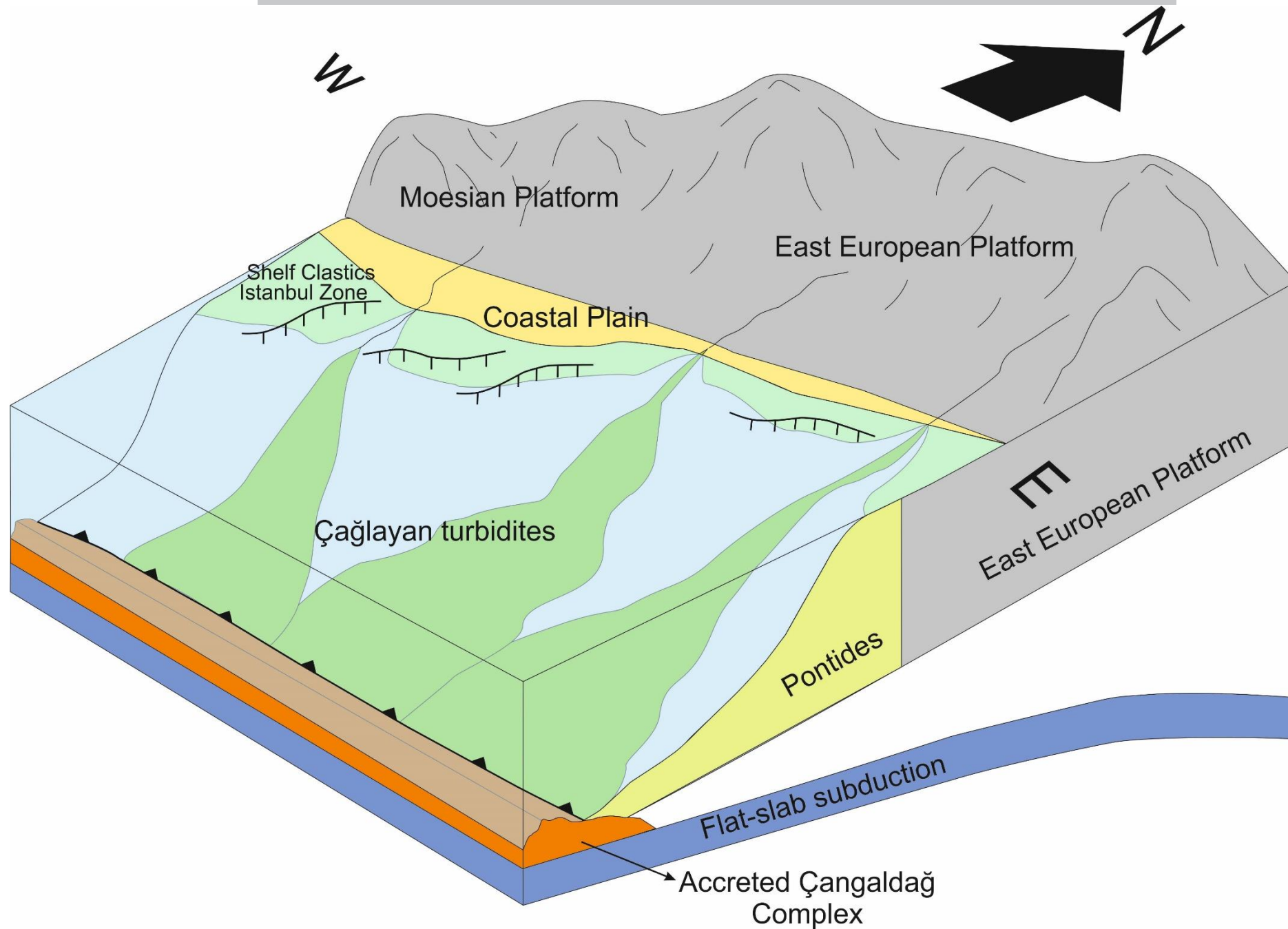


Figure16





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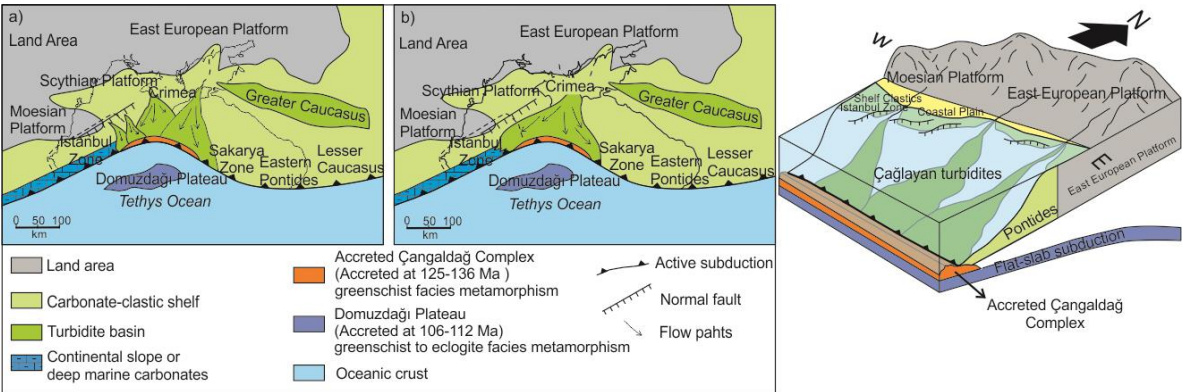




Table 1. Sample locations for U-Pb detrital zircon geochronology and detrital rutile geochemistry.

	Sample ID	Location	Latitude	Longitude	Description	Analysis	Concordant Analysis (90-110 %)	Concordant ages %
1	1A**	Sapça (Zonguldak)	41° 25' 45.90"	31° 51' 57.52"	Quartz arenite	103	80	78
2	T23	Kozlu (Zonguldak)	41° 22' 43.22"	31° 40' 43.51"	Quartz arenite	173	168	97
3	13**	Ulus (Bartın)	41° 31' 28.21"	32° 30' 31.91"	Sandstone	87	74	85
4	22A	Pınarbaşı (Kastamonu)	41° 39' 41.03"	32° 57' 13.04"	Sandstone	58	43	74
5	2221*	Azdavay (Kastamonu)	41° 31' 20.73"	33° 18' 32.87"	Sandstone	72	63	88
6	2640*	Azdavay (Kastamonu)	41° 36' 38.09"	33° 25' 01.99"	Sandstone	58	51	88
7	2721**	Ağlı (Kastamonu)	41° 36' 57.54"	33° 34' 28.17"	Sandstone	82	74	90
8	2239*	Daday (Kastamonu)	41° 26' 58.57"	33° 19' 27.78"	Metasandstone	98	89	91
9	T11	Hanönü (Kastamonu)	41° 37' 01.69"	34° 26' 50.49"	Sandstone	86	85	99
10	38**	Hanönü (Kastamonu)	41° 40' 38.76"	34° 38' 11.37"	Sandstone	101	67	66
11	T09	Çanaldag (Kastamonu)	41° 43' 14.22"	34° 38' 27.05"	Sandstone	82	77	94
12	T02	Boyabat-Gerze (Sinop) road	41° 35' 02.12"	34° 51' 02.40"	Sandstone	168	158	94
13	T03	Boyabat-Gerze (Sinop) road	41° 37'	34° 51'	Sandstone	180	165	92

			21.78"	06.71"				
					Total	1348	1194	89
*Samples used for rutile geochemistry.								
*Samples with REE abundances of detrital zircons additional to U-Pb ages.								



Highlights

1. A 400x90 km large Cretaceous submarine turbidite fan complex on the southern Laurasia margin.
2. Turbidite fan complex in the Pontides developed on the active Laurasia margin.
3. No coeval magmatic detritus in the turbidite sandstones.
4. The eastern part of the fan was fed from the Archean-Paleoproterozoic Ukrainian Shield.
5. The Black Sea opened after deposition of Lower Cretaceous (Barremian-Aptian) clastics.